RTLETT SCHOOL OF GRADUATE STUDIES

Detailed PV Cladding Design for Office Refurbishments

by

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....To my family....................

Abstract

A great concern for those aiming to reduce energy consumption in UK buildings to achieve Kyoto agreement targets should be the growing trend in installing air-conditioning in refurbishment office buildings. This study takes this challenge into account and presents an innovative cladding design for office refurbishment. The design incorporates photovoltaic power, solar control, day lighting, night ventilation and mechanical ventilation with heat recovery driven by photovoltaic power. By careful design the goal is to maximize the use of solar radiation and consequently maximize the PV energy output, maximize the use of daylight which is followed by a great decrease in electrical lighting consumption and reduce unwanted solar gains and possible glare to such an extent that mechanical heating and cooling is not significantly required to maintain comfort condition. The innovative cladding is designed for a typical assumed office module in London.

Important components of the innovative south facing cladding design are photovoltaic panels, fan including heat recovery and window with openable parts at different levels. A careful design procedure determines the optimum tilts, length, positions and shape (louvered or not) of PV panel integrated into cladding as well as percentage of glazing area. Analysis recommends that in order to maximize PV energy output, the angle of the PV cell should be flexible changing according to solar irradiation (i.e. 22.5°, 45° and 67.5°). Considering PV self shading, PV 1.60 m long generates the maximum energy output among other proposed options. Simulations indicate two positions for PV (during winter and summer time) and propose 3louvred PV panels 0.53 m long instead of a 1.60 m one.

Software simulations indicate that integrating this innovative cladding design, comfortable condition is provided with far less energy consumption compared to air-conditioned offices.

The results show that during the heating period, there are 50 hours per year when internal temperature is less than 21°C, so if occupants are prepared to accept 50 hours in a year with temperature below 21°C (e.g. by wearing more clothes), then no heating is required. If this is not the case, in order to omit entirely the need for central heating, it is proposed to use a 3 kW electric heater to provide comfort conditions. Therefore, heating consumption for this office will be 1.88 kWh/(m^2.yr). Regarding cooling requirements, it is found that due to internal gains, overheating occurs in this office, but considering that there are only 193 hours per year when external temperature goes above 25°C, it is proposed to pre-cool the incoming air when external temperature is lower than 25°C, and when external temperature is higher than 25 °C then higher fan speeds can provide extra air movement and comfort can be achieved on hot days. As ventilation consumption (i.e. 0.88 kWh/(m^2.yr)) is calculated when fan is working on its highest speed (i.e. 203 l/s, 27W), the high fan speed for cooling during hot days does not increase energy consumption.

In conclusion, this PV cladding design dose not only contribute to saving of energy for heating, cooling and ventilation compared to conventional new office facades, but also for lighting. A high degree of daylight use is enabled so that lighting energy consumption is only 6.27 kWh/(m^2.yr).

This study also compares the PV cladding design with a conventional office refurbishment option (i.e. new cladding with HVAC) regarding their cost and environmental impacts. Pollution created during manufacture is considered in terms of embodied energy and associated carbon emission. It is found that the PV panels of cladding module have a carbon payback time of 3.20 years. Implementing this innovative PV cladding design as the refurbishment option instead of the conventional system results in undiscounted saving of 377.71 and 450.08 £/m^2 without and with grant respectively during 30 years (i.e. system life time). Considering the energy price increase at its current rate (i.e. 10%), discounted saving of 377.71 and 450.08 £/m^2 (excluding and including grant respectively) can be achieved during 30 years. Also, this innovative cladding results in 97% decrease in annual CO_2 emission related to heating, cooling and ventilation compared to that of a conventional one. As the analysis shows, a big advantage of this cladding system is that there is entirely no need for any HVAC systems, therefore this innovative cladding design can reduce capital cost and minimize office energy consumption as well as CO_2 emissions.

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1. Introduction

This chapter introduces the purpose of the study; explains its aim, objectives and importance, and includes a review of other research done in this field. It also presents what the author is going to do, and explains the methodology of this study. Finally as the result of project importance it gives a summary of climate change, Kyoto protocol and consequently what UK government has to do to achieve the Kyoto agreement targets.

1.1. Importance, aims and objectives of the study

In UK, office buildings are one of the largest energy consuming sectors (Thomas and Fordham 2005). So any reduction in energy consumption in offices contributes to a significant impact on national emission rates. Nowadays, the demand on thermally comfortable condition in offices is increased, and a research study by BRECSU[1] (Anon 1995) shows that over the last decade, the use of air-conditioning in offices has increased by a factor of three in UK, and air-conditioned spaces now represent approximately 15% of UK office spaces. This increase is prompted for a variety of reasons; including client demand, increase of external pollution and noise, higher internal heat gains and hot summers. These reasons encourage owners to install air-conditioning equipment which consumes a great amount of energy to provide comfortable condition. However, the same study shows that occupants often prefer a degree of control to the less user-orientated control structure of conventional air-conditioning installations. Moreover, existing offices undergo refurbishment from time to time to upgrade their internal and external environment to provide more modern accommodation and to attract new owners; therefore energy efficient office refurbishment can make a significant reduction in national emission rates.

On the other hand, as Thomas et al (1999) mention solar energy plays an ever-increasing role in generating the form and affecting the appearance and construction of buildings. The principal reason for this is that photovoltaic systems are becoming more widespread as their advantages become evident and costs decrease.

Therefore, this study proposes an innovative photovoltaic cladding design which is an approach to provide an energy efficient strategy for office façade refurbishment; however, it has the potential to be applied in new designs as well. This innovative cladding differs substantially from conventional office façade. One of its objectives is to provide comfortable level for occupants to increase satisfaction and productivity. The design addresses all the related issues like thermal comfort, indoor air quality, acoustic quality and lighting, local control over conditions and view to outside. It not only provides comfortable condition, but also aims to reduce heating, cooling, ventilation and lighting energy consumption, and by considering photovoltaic as a form of cladding integrated renewable energy, it generates electricity as well.

To achieve its aim, the cladding unit is a modular façade unit for a south facing façade that aims to eliminate air-conditioning system by incorporating maximum use of solar energy and daylight, controlling solar gain and reducing overheating. A modular concept is adopted for the cladding unit to solve the technical challenges of integration and operation of the cladding in a wider context of office buildings.

It is recognized that there is recent related research, supported by different organizations, on innovative facade designs based on philosophy of reducing the energy needs of buildings, which again shows the importance of this innovative approach. One research, supported by DETR[2], is the design of a prototype unit, done by Palmer, Perera and White (2003), which incorporates PV panel (acts as solar shading and generates electricity for fan), window openings (provide fresh air and night cooling), trickle ventilator (provides comfort cooling). The design controls heat gains and losses and provides adequate daylight and natural ventilation. There is another study, supported by the German Federal Ministry of Economics and Technology, which is the design of a façade which contributes to the halving of lighting and heating costs, done by Häusler and Berger (2006). The design incorporates air-collectors (supplies preheated air), fan with heat recovery (pre-heat and pre-cool the air), PV elements (generate electricity).

In order to reduce office building energy consumption and consequent CO_2 emissions it is essential to minimize the need for an air-conditioning system. The next section presents what the author is going to do to achieve the research aims and objectives.

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1 - Building Research Energy Conservation Support Unit

2 - Department of Environment, Transport and Regions

1.2. Methodology

To design this innovative cladding in proper procedure, it is necessary to first outline comfortable condition in office spaces and to verify commonly accepted parameters; including thermal comfort, indoor air quality, acoustic quality, lighting quality and occupants' control. As the design must address guidelines and recommendations of various studies in the review, it is proposed to investigate all related regulations and recommendations on elements integrated into this cladding module. In particular, the amount of adequate supplied fresh air, daylight, glazing area, material thermal properties, efficiencies of integrated devices (i.e. photovoltaic, fan, heat recovery, etc).

Regarding the design of PV cladding, it is proposed to design the cladding module for the south façade of an assumed office space in an office building.

The first principal issue to design this cladding module which needs a detailed investigation is the incorporation of the PV panel to generate maximum possible electricity. The variation of electrical power generation from the PV system during one year is investigated considering the influence of the inclined PV panel on its energy output to verify the optimum tilts of PV panel. Also the influence of the shadow cast by other PV panels of different lengths is carefully considered during the design phase to find out the optimum length for PV panel. In order to assess the optimum position of the PV panel integrated into cladding, different models are simulated in thermal and lighting tools (i.e. TAS and AGI32) to find out the optimum position of PV regarding internal energy requirements. Detailed lighting simulations are proposed to calculate the daylight factor and electrical lighting design of assumed office module. Detailed investigation and simulations are also suggested to assess supply air condition to verify if heat recovery and night ventilation help to cut energy requirements.

Based on simulations and investigations, architectural design of innovative PV cladding design following its performance during the whole year, its energy consumption and internal conditions are considered. Finally, cost and environmental impacts of the design are analyzed, the main focuses are carbon and economic impacts of innovative façade design, and social impact is not considered.

Following section presents climate change and factors involved in it.

1.3. Climate change

The basic mechanics of climate change are well understood; the world is warming, studies by Grubb (2005) show that much of the warming is due to human emissions of greenhouse gases, and the changes are set to accelerate in the future, causing varied impacts around the world. The same study shows that over the past 140 years the earth's surface temperature is increased on average by 0.6±0.2°C with the greatest increases occurring the second half of the last century; (i.e. the 1990s; the warmest years in history). Although this rise in temperature might appear small, it is scientifically significant and has dramatic impacts on climate. Figure 1.1 and 1.2 present variations of earth's surface temperature during past 140 years and 1000 years respectively.

Figure 1.1: Variation of the Earth's surface temperature for the past 140 years (Houghton 2001, p.3)

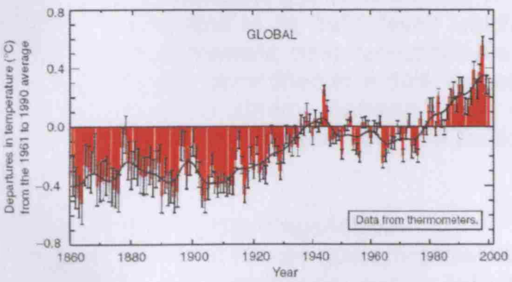
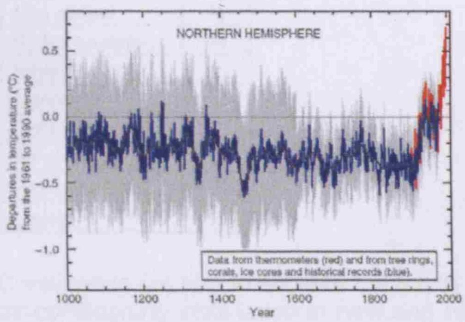


Figure 1.2: Variation of the Earth's surface temperature for the past 1000 years (Houghton 2001, p.3)



As Grubb (2005) mentions, since 1950s scientists have observed the retreat of mountain glaciers, a shrinking of the Artic ice cap as well as a lengthening of the freeze-free season. Warming increases evaporation and precipitation, and both aggregate rainfall and occurrences of heavy precipitation events at European latitudes, the principal cause of flooding, has also increased in recent decades. There is also evidence that the frequency and intensity of storms is increasing in certain areas. Although it is difficult to obtain accurate predictions on the impacts of climate change, research by Grubb (2005) shows that climate models foresee a global temperature rise in the range of 1.4 - 5.8°C by 2100 if current greenhouse gas emission trends remain unchecked. Even if some measures are taken, the effect will continue for centuries. Grubb (2005) expects the impacts of even a small increase in temperature to be significant and to include:

- Flooding in coastal areas
- Wetter, warmer winters and dryer, hotter summers in the Northern Hemisphere
- More extreme weather conditions worldwide (storms, drought, heavy rainfall)

Considering word climate change, the Kyoto protocol, an international agreement, sets targets to reduce greenhouse gas emissions of developed countries, the next section discusses the Kyoto protocol.

1.4. The Kyoto protocol

The Kyoto Protocol, agreed in 1997, is an international agreement setting targets for industrialized countries to cut their greenhouse gas emissions, which is considered to be at least partly responsible for global warming. As Blundell (2000) mentions some 141 countries, accounting for 55% of greenhouse gas emissions, have ratified to cut these emissions by 5.2% by 2012 (compared to their 1990 level). So each country that signed the protocol, agreed to its own specific target. EU countries are expected to cut their present emissions by 8%; and the UK's international legal obligation is a reduction of greenhouse gas emissions by 12.5%, but UK adopted a voluntary goal of a 20% reduction by 2010 (compared to its 1990 level) which is much more ambitious (BBC 2006). In addition, to stabilize the atmosphere, deep reductions are required; according to Blundell (2000) the UK and other EU countries are committed to a 60% reduction in carbon emissions by 2050 and perhaps an 80% reduction by 2100. Energy demand in UK office buildings and its consequent impacts on global climate change is considered in the next section.

1.5. UK Building Regulation

Achieving above mentioned goals requires vision, leadership, and action, so UK, responsible for about 3% of global CO_2 emissions, aiming to achieve the Kyoto agreement targets is setting building regulations. Building regulations are designed to improve energy performance of buildings. It is important to know the effect of buildings on energy use and carbon dioxide emissions. According to Thomas and Fordham (2005), in the UK about 45-50% of delivered energy use and just under 50% of all CO_2 emission is accounted to buildings. Approximately 60% of building related CO_2 is due to the domestic sector and about 30% is attributed to the service sector (i.e. UK public and commercial buildings). In the service sector the total CO_2 emission is about 89 million tones and approximately 44% of this is due to space heating. Table 1.1 presents CO_2 emission of each end use in UK service sector.

Table 1.1: Carbon dioxide emission by end use for the UK service sector (Thomas and Fordham 2005, p.30)

Use of fuel	%
Space heating	44
Water heating	7
Lighting	17
Cooking	6
Air conditioning	6
Refrigeration	7
Power	13

Considering UK aim to achieve the Kyoto agreement targets and reducing energy use in buildings, the air-conditioning installation in new and refurbished office buildings will be a major concern. Most air-conditioned buildings are completely sealed off from the outside and air is supplied from a central air-handling unit. Heat from the sun, equipment and occupants have to be removed by air from the central plant and this necessitates a cool air supply and requires energy. So energy for cooling, its equipments and lighting are areas where significant reduction can be made to reduce energy consumption of air-conditioned buildings.

This chapter discusses aims and objectives of the study and describes UK role in reducing global warming, next chapter describes energy requirements to provide comfort condition in offices and explains recommended comfortable conditions.

2. Office energy requirements and comfort condition

This chapter gives a brief summary of important issues when considering office energy consumption. It first describes all end uses for energy in air-conditioned offices and discusses the 4 end uses for energy which are considered in this study. Based on recommendations of CIBSE[1] guide A it explains comfort condition in office buildings as well.

2.1. Energy consumption in office buildings

According to ECON19[2] (Anon 2003a), there are nine principal end uses for energy in office buildings relating to building services or occupiers' equipment.

End uses (building services):

- Heating and hot water
- Cooling
- Fans, pumps and controls
- Humidification
- Lighting

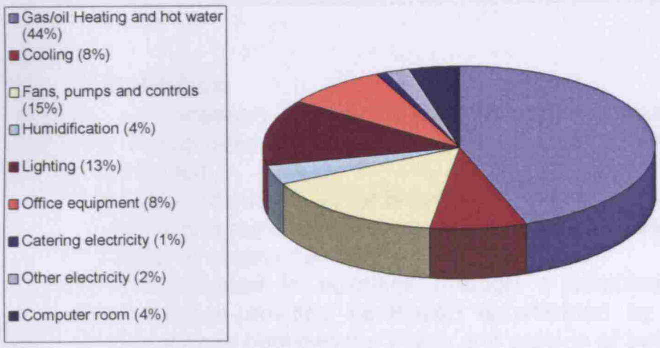
End uses (occupiers' equipment):

- Office equipment
- Catering
- Other electricity
- Computer and communications rooms

Based on data in ECON19 (Anon 2003a), in naturally ventilated offices, heating is the largest single energy cost item and in the others lighting, fans and computer rooms are of greater or equal importance. Studies (Anon 1993) show that recent offices have better insulation, boilers and controls so they use significantly less heating fuel than the average. But, due to more information technology, more permanent artificial lighting and more air conditioning, their electrical consumption is often higher.

As chart 2.1 shows, in air-conditioned offices, one of the largest single components of electricity energy consumption is lighting, also electricity used by fans and pumps is significant. Therefore, when considering the task of improving the energy efficiency of an office building, the reduction of lighting energy use and avoidance of air-conditioning should be targeted to ensure maximum returns.

Chart 2.1: Percentage of delivered energy used by each end use in a typical air-conditioned office (Anon 2003a)



Of the uses mentioned above, only the following 4 end uses for energy in office buildings are considered in this study.

- Heating
- Cooling
- Ventilation
- Lighting

Together they cover approximately 80% of delivered energy in a typical air-conditioned office.

1 - Charted Institution of Building Services Engineers

2 - Energy Consumption Guide 19

2.2. Heating

The use of fuels or electricity to heat above 19 °C is prohibited by the Fuel and Electricity (Heating) (Control) Order (1974) and the Fuel and Electricity (Heating) (Control) (Amendment) Order (1980) (cited Humphreys et al 2006). Humphreys et al (2006) explain that this does not mean that the temperature in buildings must be kept below 19 °C but only that fuel or electricity must not be used to raise the temperature above this level. CIBSE guide A (Humphreys et al 2006) recommendation on winter design temperature in offices exceeds 19 °C. In this case, it is assumed that the recommended temperatures can be maintained by heat sources other than heating system. These might include solar radiation, heat gains from occupants, lighting and equipments.

2.3. Cooling

Summer comfort temperatures given in CIBSE guide A (Humphreys et al 2006) (i.e. 22-24°C) applies to air-conditioned offices, but the same guide explains that higher temperatures might be acceptable if full air-conditioning is not present. For non air-conditioned offices, table 2.1 indicates acceptable values for general summer indoor temperatures. However, providing these summer internal design standard without mechanical cooling might not be possible under all conditions, and it is necessary to analyze the risk of overheating and to minimize the length and intensity of possible discomfort. In UK, according to CIBSE guide A (Humphreys et al 2006) in non air-conditioned office buildings, 25 °C is an acceptable indoor temperature during warm summer weather, and few people will be uncomfortable at this temperature. But if indoor temperature goes above this value occupants might be uncomfortable and there might be a decrease in the productivity of office work. The same guide recommends that peak temperature during the day should preferably not be more than 3 K above the design temperature, giving a benchmark maximum of 28 °C as presented in table 2.2.

Table 2.1: General summer indoor comfort temperature for non air-conditioned office (Humphreys et al 2006, p.1.11)

Building type	Operative temp for indoor comfort in summer (°C)	Notes
Offices	25	Assuming warm summer conditions in UK

Table 2.2: Benchmark summer peak temperature and overheating criteria (Humphreys et al 2006, p.1.12)

Building	Benchmark summer peak temperature (°C)	Overheating criterion
Offices	28	1% annual occupied hours over operative temperature of 28 °C

2.4. Ventilation

Ventilation is necessary to remove stale indoor air, provide fresh air and control thermal comfort. According to approved document F1 (Anon 2006a), Ventilation is required for one or more of the following purposes:

- Provision of outside air for breathing
- Dilution and removal of airborne pollutants, including odours
- Control of excess humidity

Ventilation is provided in buildings through a combination of infiltration and purpose-provided ventilation. Purpose-provided ventilation is provided by natural and/or mechanical devices and controls air exchange between the inside and outside of building.

2.4.1. Minimum ventilation rates for air quality

Ventilation minimizes the concentration of harmful pollutants, therefore higher ventilation rates are usually accompanied with improved health. The amount of ventilation required for air quality depends on occupant density and activities as well as pollutant emissions within the space (Anon 2006a). The whole building ventilation rate for the supply of air to offices should not be less than that specified in table 2.3.

Table 2.3: Whole building ventilation rate for air supply to offices (Anon 2006a, p.23)

	Air supply rate
Total outdoor air supply rate for offices (no smoking and no significant pollutant sources)	10 l/s per person

According to Gold and Martin (1998), where heat gains are above 30 W/m^2 and the plan depth is greater than 7 m for single sided ventilation (12 m for cross-ventilation), then natural ventilation is unlikely to be suitable on its own and a mixed mode solution or full use of mechanical system is required. Mechanical ventilation is also required where there is high occupant density and it is not possible to introduce adequate natural ventilation without causing draughts. Table 2.4 presents benchmark allowance for internal heat gains in typical office buildings in city centre.

Table 2.4: Benchmark allowances for internal heat gains in office buildings (Humphreys et al 2006, p. 6.3)

Building type	Use	Density of occupation (m^2/person)	Sensible heat gain (W/m^2) People	Lighting	Equipment	Latent heat gain (W/m^2) People	Other
Office	City centre	6	13.5	8-12	25	10	-
		10	8	8-12	18	6	-

When mechanical ventilation is provided, filter is necessary. Following sub-section discusses filter.

2.4.2. Filter

Filters provide a significant resistance to airflow. CIBSE guide F (Jones et al 2004) recommends that a careful balance should be between filtration efficiency and pressure drop. The same guide presents BSRIA[3] analysis of whole life performance of filter systems (i.e. the balance between space and capital costs and the operating costs such as inspection). The conclusion is that filter performance depends not only on the filter specification but also on the design and installation of the filter system. Poor filter installation neutralizes the benefits of specifying good filters. CIBSE guide B (Henderson et al 2005) recommends that the overall efficiency for the filter installation must be not less than that specified for the filter. The same guide generally suggests that:

- Air intakes should be located away from the direction of the prevailing wind to prolong filter life and improve the quality of the intake air
- Air filters should be protected from direct rain by using weather louvres
- Filters should be installed upstream of mechanical equipment to provide protection for that equipment; a final filter should be located downstream of the fan under positive pressure to reduce the risk of dust entering the system downstream of the filter
- Adequate access for cleaning should be provided

Noise from building services should be minimized as far as possible; the following sub-section gives necessary recommendations.

2.4.3. Acoustic control of building services

There are a large number of potential noise sources in building services installation including fans, duct components, grilles, diffusers and etc. The tendency away from central plant to local systems brings noise sources closer to occupants and increases the problems of noise reaching occupied rooms. According to Burton (2001) ventilation systems can produce two sorts of noise problems. Structure-borne sound is sound produced by the fan, motor and compressor and aerodynamic noise which is transmitted via the ducts to other parts of the building is sound produced by high velocity air in the ducts.

Fan noise

According to Henderson et al (2005) control of fan noise depends on:

- Choosing an efficient operating point for fan
- Design of good flow conditions
- Ensuring that the fan is vibration isolated from the structure
- Ensuring that the fan is flexibly connected to the duct

Grills and diffusers noise

Control of air velocity and flow conditions is the key to reduce this noise and manufacturers' data should be consulted. Once the sound enters the room, there is no further attenuation other than room surface absorption, so grilles and diffusers are the last stage in noise control.

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2.5. Lighting

An important factor in any energy efficient building strategy is lighting control or specifically the effective daylight utilization. Additionally, lighting controls play an important role in turning the lighting off when the space is unoccupied, so lighting energy consumption and its heat gains are reduced. Studies (Anon 1995) show that user education helps to make maximum benefits from daylight. Lighting requirements related to each activity is presented in table 2.5. As it shows required illuminance in offices is between 300-500 lux.

Table 2.5: Examples of activities/interiors appropriate for each maintained illuminance*(Humphreys et al 2006, p. 1.22)

Standard maintained/ illuminance (lux)	Characteristic of activity/ interior	Representative activities/ interiors
300	Continuously occupied interiors, visual tasks moderately easy, i.e. large details > 10 min. arc and/or high contrast	Libraries, sports and assembly halls, teaching spaces, lecture theatres, packing
500	Visual tasks moderately difficult, i.e. details to be seen are of moderate size (5–10 min. arc) and may be of low contrast; also colour judgment may be required	General offices, engine assembly, painting and spraying, kitchens, laboratories, retail shops

* Maintained illuminance is defined as the average illuminance over the reference surface at the time maintenance has to be carried out by replacing lamps and/or cleaning the equipment and room surfaces

When providing adequate illuminance in office, the actual installed power should be known. Table 2.6, which illustrates target installed power densities for various task illuminances, can be used where the actual installed power is not known.

Table 2.6: Lighting energy targets (Humphreys et al 2006, p. 6.4)

Application	Lamp type	Task illuminance (lux)	Average installed power density (W/m²)
Commercial and similar applications (e.g. offices, shops*, schools)	Fluorescent-triphosphor	300	7
		500	11
		750	17
	Compact fluorescent	300	8
		500	14
		750	21
	Metal halide	300	11
		500	18
		750	27

* Excluding display lighting

2.6. Designing for comfort

Air-conditioned offices use a lot of energy to provide comfort condition. Studies by Rennie and Parand (1998) shows that air-conditioned offices are often linked to lack of comfort compared to naturally ventilated buildings. The same study presents that in one UK survey; approximately 55% of staff in air-conditioned buildings are affected by SBS[4]. However, the study does not prove the link between air-conditioning and SBS and it is difficult at present to be definitive about the causes of SBS.

Basically, occupants' expectation of a comfortable and healthy environment is linked with productivity, so office designs should consider the issues of productivity, health and comfort of the occupants at the same time as the energy efficiency of the building. According to studies (Anon 1995) occupants' desire to control heating, cooling, lighting and ventilation in the work space influences the perception of the quality of the internal environment. In order to prevent the abuse of environmental systems and energy wastage, a degree of individual control is essential, but it should be kept within the constraints of overall effective management. Recommendations on comfort criteria for offices are presented in table 2.7. As the table shows, the highest temperature during summer is 24°C, but this applies to air-conditioned office space and as mentioned previously higher temperature is acceptable in non air-conditioned offices.

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Table 2.7: Recommended comfort criteria in offices (Humphreys et al 2006, p. 1.9)

Building	**Winter temperature range**			**Summer temperature range (air-conditioned buildings)**			**Suggested air supply rate (l/s.p)**	**Filtration grade**	**Maintenance illuminance (lux)**	**Noise rating (NR)**
Offices:	Temp (°C)	Activity (met)	Clothing (clo)	Temp (°C)	Activity (met)	Clothing (clo)				
Executive	21-23	1.2	0.85	22-24	1.2	0.7	10	F7	300-500	30
General	21-23	1.2	0.85	22-24	1.2	0.7	10	F6-F7	300-500	35
Open-plan	21-23	1.2	0.85	22-24	1.2	0.7	10	F6-F7	300-500	35

The principal aim of this study is to develop a cladding solution that provides a high level of comfort and fresh air while at the same time consumes less energy. The benefits of cladding solution can include lower running and maintenance costs, possibly less capital outlay, increased useable area with fewer plant rooms, and the potential for increased occupant satisfaction when given local control over internal environmental conditions.

In this chapter office energy requirement regarding heating, cooling, ventilation and lighting as well as comfort conditions are explored. Next chapter discusses detailed recommendations on each component integrated into the cladding design.

3. Components of a zero energy façade for UK offices

The facade serves many purposes. It provides external aesthetic value of the building and the point of entry into building. It may allow ventilation and natural light to enter. It can incorporate solar shading, noise attenuation, insulation against heat loss and heat gain, and collect solar power for electricity generation.
The previous chapters lay out the situation where existing UK offices use high and increasing amounts of energy to provide comfort conditions, where it might be possible to refurbish some of these offices with a low or zero energy façade to dramatically reduce the energy consumption while providing improved comfort conditions.
This chapter discusses components integrated in a façade which provides fresh air from outside, which is filtered from pollution and noise, and heated or cooled as necessary only using power generated from itself. Each façade module is self powered so needs no electrical connection to the building or to neighbouring modules. Photovoltaic panels provide electricity, and also shade the window elements, a heat recovery fan (if necessary) removes exhaust air and this is also used to pre-treat the incoming air. Individual components are discussed in detail in this section.

3.1. Non-glazed portions of facade

In this part elements U-Value and materials for non-glazed portions are discussed.

3.1.1. Elements U-Value

Each façade module needs to be designed such that the whole building achieves UK building regulations. The building regulation, part L (Anon 2006b) sets out limits on design flexibility that are considered reasonable for the purposes of achieving the energy efficient requirements.

Table 3.1: Limiting U-Value standards (Anon 2006b, p.21)

Element	Area-weighted average U-Value (W/(m^2.K))	Limiting U-Value (W/(m^2.K))
Wall	0.35 (0.30)*	0.70
Floor	0.25 (0.22)*	0.70
Roof	0.25 (0.16)*	0.35
Windows, roof windows, roof lights and doors	2.20 (1.80)*	3.30

* U-Values in the parenthesis are given by Lowe (2006)

3.1.2. Non-glazed portions

Material used in window frame and non-glazed portion is proposed to be recycled aluminium with thermal break. According to technical information (Schueco 2006), aluminium profiles for windows and façades are double-chambered and rolled together with insulating bars, and aluminium has the advantages that it is light, maintenance free and long life. It can be extruded with precision to make energy-saving building components sealed against the elements and with a high degree of sound and thermal insulation. Additionally, the same technical information states that over 60% of the energy required to extract aluminium worldwide is generated from environmentally friendly renewable sources, namely water power, and after recycling, used aluminium still retains its quality characteristics and when used aluminium is melted down only 5% of the original energy input is required. For details on selection of recycled aluminium as window frame material see appendix A.

3.2. Glazing

In this part maximum allowable glazed area, glazing material and window openings are discussed.

3.2.1. Maximum allowable glazed area

Glazed surface might cause heat losses and overheating thus additional heating load in winter time, and cooling load in summer time respectively, therefore the building regulations, part L (Anon 2006b) sets out limits on the maximum area of windows in order to reduce heat losses and heat gains through glazed elements unless it is compensated in a better way like providing renewable energies. Table 3.2 gives maximum area of glazed opening, set out in the building regulation part L, which is depended on the orientation and is expressed as a percentage of the area (measured internally) of the wall in which it occurs.

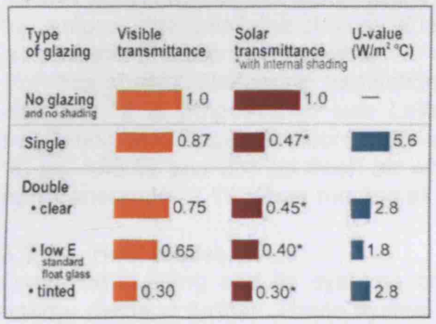
Table 3.2: Maximum allowable area of glazed opening in offices (Waters 2003, p. 49)

Orientation of glazed opening	Maximum allowable area of opening (%)
North	50
North-east, north-west, south	40
East, south-east, west, south-west	32
Horizontal	12

3.2.2. Glazing material

The choice of glazing affects the daylight, solar heat gain and heat loss through a window. These are measured by visible transmittance, total solar transmittance and U-Value. Double glazing gives about 15% less daylight than single glazing, but it halves heat loss. According to Rennie and Parand (1998), using low-e glass reduces the heat loss from a double glazed window by about a third, but with the penalty of a further small loss in daylight. Tinted glazing reduces solar heat gain and cannot control glare from the sun. CIBSE guide A (Humphreys et al 2006, p.1-23) presents approximate diffuse transmittance for more various glazing types, as it shows the U-Value of a triple glazing is the same as that of a double glazing (low-e), which is 1.8 W/(m^2.K). Figure 3.1 illustrates transmittances and U-Value of some common types of glazing and the no glazing option is to help to define full transmittance.

Figure 3.1: Transmittances and U-Value of some common types of glazing (Rennie and Parand 1998, p.48)



Based on transmittances and U-Value of different glazing type, low-e double glazing (U-Value: 1.80 W/(m^2.K), 0.65 visible transmittance and 0.40 solar transmittance) is proposed as glazing material of this cladding design.

3.2.3. Window openings

This study concerns façade components, and windows are one of the main parts of façades. Windows shape and openings are considered in detail in appendix B. In summary separate opening elements at different levels are suggested in this study to provide necessary requirements, i.e. a small adjustable opening close to ceiling to provide night ventilation in summer and a small opening just above sill height to provide extra year-round ventilation. For details on window openings see appendix B.

3.3. Ventilation system

Uncontrolled ventilation should be reduced or prevented. Elements need to fit very well to prevent air infiltration. Night ventilation as a means of natural purpose-provided ventilation, and fan and heat recovery as a mean of mechanical ventilation are considered in this part.

3.3.1. Night ventilation

Night ventilation is one of the most efficient passive cooling techniques. As Irving et al (2005) mention, by cooling the fabric of the building by night ventilation, there is a reduction in the mean radiant temperature of the space, which enhances the occupants' perception of thermal comfort during the following day. According to Irving et al (2005), night ventilation involves some additional issues that need to be considered as part of the briefing and design process which include the following:

- Night ventilation via opening windows is a security risk; this can be overcome by using opening limit devices, separate ventilation openings
- Appropriate controls are needed to avoid over cooling the space, with subsequent discomfort the following morning

- Good thermal contact (and thus high heat transfer rates) must be ensured between the ventilation air and the thermally massive elements of the building

Concrete structure and ceiling slabs offer an ideal thermal mass which can be used as thermal store in this study.

3.3.2. Fan

Mechanical ventilation installation increases capital, maintenance and running costs as well as environmental emissions (Jones et al 2004). Therefore, mechanical ventilation rates should be kept to minimum with acceptable levels of indoor air quality, and the size of fan, fan power usage and ventilation heating/cooling loads should be kept to a minimum. As Jones et al (2004) explains energy can be wasted in ventilation system by:

- Poor fan efficiency
- Unnecessary bends
- Reduced duct size
- Excessive duct length
- Poor inlet and outlet conditions
- Accumulation of dirt

A large proportion of the total energy in mechanically ventilated buildings is consumed by fans. Henderson et al (2005) present different fan types showing their relative efficiencies, advantages and disadvantages, but all the presented fans refer to central ventilation systems and are not appropriate for the application of this study which is to provide a local ventilation system. So in order to select a fan among other available choices, it is propose to choose the most efficient one with the size as close as possible to the actual demand.

For this study, considering ventilation requirement (i.e. 80 l/s) which is explained in the following chapters, it is proposed to use LoWatt TX9WL fan, which is a high performance extract/intake ventilating unit. Appendix C presents characteristic of selected fan. As it shows selected fan provides 90 l/s, 156 l/s and 203 l/s fresh air when running at its low, medium and high speed respectively. It only consumes 27 W, when running at its high speed.

3.3.3. Heat recovery

Once the building and its systems are efficient, recovering heat can be considered to reduce the energy demand further. These systems most commonly recover heat from ventilation systems, using devices such as heat wheels or run-around coils to recover energy from exhaust air, then use it to pre-heat or pre-cool supply air. A study (Anon 1993) shows that in offices, the scope for this is often limited, because the heat available is normally low, the demands can be low both in quantity and in time, and electrical costs of it can be relatively high. But in some cases, considering heat recovery can reduce the overall capital and running costs of the building services. According to Jones et al (2004), the likelihood of cross-contamination between air streams and the extra power consumption of fans to overcome additional air resistance are key considerations.

Heat recovery within mechanical ventilation systems becomes economic when the value of the recovered heat outweighs the increase in fan capital and running costs, as well as those of the heat recovery equipment. It is also important to note that extra fan power is needed whenever the system is in operation, although the degree of heat recovery varies throughout the year. Typical heat recovery devices mentioned by Barnard et al (2001) include:

- Run-around coils
- Thermal wheels
- Plate heat exchangers
- Heat pipes
- Heat pumps
- Air re-circulation

But most of the heat recovery devices presented by Barnard et al (2001) refer to central systems and plate heat exchangers is the only device which can be used as a local heat recovery system in this study. Appendix D first presents technical consideration in order to select a heat recovery device in general and then describes plate heat exchanger, as it shows plate heat exchanger is 70% efficient. Filtration and noise control of ventilation should be considered when providing mechanical ventilation and are discussed in previous chapter (Chapter 2, p.7).

3.4. Lighting consideration

It is required for each façade module to provide view and adequate daylight, remove glare and ensure privacy. Daylight not only provides potential energy savings but it improves occupant sense of well-being. Research (Anon 2003b) shows that everyone prefers to work in daylit spaces although the exact reasons are unclear. Windows need to strike a balance between providing optimum daylight, view, and useful solar gains in winter, while avoiding glare, overheating in summer and being too cold surface in winter. Therefore, solar control is particularly important. Gold and Martin (1999) present the four principal solar control methods as:

- Internal shading devices (normally blinds)
- Mid-pane shading devices (blinds)
- External shading devices (including shutters, fixed louvres, blinds, fixed projections, canopies, trees)
- Solar control glass

The type of solar control used depends upon the orientation of the facade, glazed area, budget, and any other restrictions. As a rough guide Kendrick et al (1998) recommends that glazed areas under 20% of wall area require no solar control, glazed areas of 20% to 50% can use internal shading, and anything over 50% may require external shading to keep internal conditions comfortable in summer. Table 3.3 presents advantages and disadvantages of some solar control options. As it shows controllable external devices generally have more advantages than other options.

Table 3.3: Advantages and disadvantages of some solar control options (Buck 2006)

	Double clear glass	**Treated glass**	**Internal blinds**	**External blinds**	**Brise soleil**	**fixed external fins**	**Controllable external fins**	**Internal light shelves**
Solar gain reduction	N/A	Moderate to good	Moderate	Good	Good	Good	Excellent	Moderate
Glare reduction	N/A	Good	Moderate to good	Moderate to good	Moderate	Moderate	Good	Good
Vision out	Excellent	Good	Poor to moderate	Poor to moderate	Good to excellent	Moderate to good	Good	Good
Privacy	N/A	Moderate to good	Good	Good	N/A	poor to moderate	Good	Moderate
Security	N/A	N/A	N/A	N/A	Poor	Poor to moderate	Good	Moderate
Maintenance of daylight	Excellent	Variable	Moderate to poor	Moderate to poor	Moderate to good	Moderate to good	Good	Good
Wind resistance	N/A	N/A	N/A	Poor	Good	Good	Good	N/A
Architectural feature	N/A	Possible	No	Possible	Yes	Yes	Yes	Possible
Unobtrusive	Yes	Possible	Yes	Possible	No	No	No	No
Suitable elevations	All	All	All	All	SE-SW	All	All	All
Synergy with natural ventilation	N/A	Moderate	poor to moderate	Poor to moderate	Good	Good	Good	Good

Moreover, in order to design electrical lighting considering daylight, it is important to find out the average daylight factor. The average daylight factor (D) is used to predict the extent to which daylight is a significant factor in the lighting of the building. It applies to cloudy climates where skylight is employed as the main source of natural light. In general according to Tregenza and Loe (1998) if daylight factor is less than 2% then electric lighting is likely to be needed in the space during daytime hours, and will appear dominant; between 2% and 5%, supplementary lighting might be needed during daytime but the room appears to be daylit; above 5%, electric lighting will not normally be necessary but thermal problems become likely.

3.5. Photovoltaic system

If the 19th century was the age of coal and the 20th of oil, the 21st is the age of the sun (Thomas et al 1999). Solar energy plays a significant role in generating the form of buildings and PV[1], an advanced materials technology which produces electricity from solar energy, helps to design buildings which are environmentally responsive and exciting. In this part, common PV cell types, its forms and systems

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and factors affecting its energy output as well as its cost and environmental impacts are considered in general.

3.5.1. Common PV cell types

At present the most common PVs are based on silicon. Common PVs available are monocrystalline silicon, polycrystalline silicon and thin film silicon (using amorphous silicon). A typical crystalline cell might be 100 mm by 100 mm and cells are combined to form modules. Table 3.4 presents properties of common PV cell types.

Table 3.4: PV cell and module data (Thomas and Fordham 2005, p.256)

Type	Approximate cell efficiency (%)	Approximate module efficiency (%)	Approximate installed cost (£/Wp)	Construction
Monocrystalline silicon	13-17	12-15	10	Single silicon crystal
Polycrystalline silicon	12-15	11-14	5.8-6.9	Cast ingots of many crystals
Thin-film silicon	5	4.5-4.9	5.8	Stack of series of p-n layers, so responsive to large band of wavelengths
Triple junction thin-film silicon	6-8	5-7	5.8-10	Three amorphous layers with different band gaps
Heterojunction with intrinsic thin layer (HIT)	17-19	14-16[e]	6.9-7.5	Monocrystalline layer in a thin-film amorphous sandwich

3.5.2. PV Forms and systems

According to Thomas et al (1999) there are three basic ways to integrate PVs into buildings:

- Roof-based systems
- Façade systems
- Sunshades and sunscreen

Since this study is PV cladding design, only façade systems are considered. Table 3.5 lists the main façade systems available.

Table 3.5: Façade systems (Thomas et al 1999, p.26)

Position of PVs	System	Characteristics and comments
Vertical wall	Curtain Walling	Standard, economical construction, PVs can be mixed, i.e. some bring opaque and some semi-transparent
Vertical wall	Rainscreen Cladding	Rainscreen designs incorporate a ventilation gap which is advantageous in getting rid of heat; the gap can also be used for running cables
Vertical wall with inclined PVs	Glazing or rainscreen cladding	PV efficiency improved Complexity of construction increased Potential to provide shading of windows (if desired) but a degree of self-shading
Inclined wall	Glazing	Potentially enhanced architectural interest PV output is improved compared with a vertical wall Less efficient use of building floor area
Fixed sunshades	Glazing	Can enhance architectural interest Entails a loss of daylight
Moveable sunshades	Glazing	Can enhance architectural interest Entails some loss of light but less than fixed shades Increased PV output compared with all fixed systems

3.5.3. Factors affecting energy output of PV array

Solar radiation, shading, soiling, PV cell temperature, mismatch and sizing are factors affecting energy output of PV array. Appendix E discusses these factors in detail and presents advantages of BIPV[2] systems.

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3.5.4. Cost of BIPV systems

BIPV systems are still expensive although costs have been going down. Generally, building integrated PV systems are not cost-effective, however where PVs replace a range of expensive, prestige cladding, they are expected to be cost-effective. PV-integrated buildings are expected to become commercial realities by 2010 (Thomas et al 1999). Table 3.6 provides some cost comparisons. It is important to note that these are for illustration only and it is necessary to obtain up-to-date cost estimates when considering cost analysis.

Table 3.6: Approximate costs for BIPV systems and comparison with conventional building elements (Rawlings and Roper 2000, p.6)

System/element	Installed cost (£/m^2)
Wall systems	
PV curtain walling, glass/glass crystalline modules	780
PV curtain walling, glass/glass thin film amorphous modules	250
Conventional wall systems:	
Double glazing cladding system	350
Cavity wall (brick exterior/block interior)	50-60
Stone cladding	300
Granite faced pre-cast concrete cladding	640
Polished stone cladding	850-1500
PV rain screen cladding	600
Steel rain screen over cladding	190
Roof systems	
PV roofing tiles (housing estate)	500
Roofing tiles (clay or concrete)	32
PV modules on a pitched roof (large office)	650
Aluminum pitched roof	44

Note: Costs for PV systems assume crystalline silicon technology except where otherwise stated and include balance of the system (BOS) costs.

3.5.5. Environmental impacts by PV systems

Environmental impacts caused by PV systems can be divided into two categories:

- Impacts from production of the components of a PV system
- Impacts from the daily operation of the PV systems

Environmental impacts due to manufacturing of PV systems

The most common solar cell material is silicon which is a chemical industry product. According to Goetzberger and Hoffmann (2005), solar cell manufacturing requires diffusion, oxidation, and contacting steps for which different chemical are employed. They are either recycled or disposed in a very controlled manner. Cells or modules that are damaged during production are recycled into the process. The inverter like other electronic equipment is manufactured under the same standards of environmental protection. Therefore, it can be stated that there are no environmental impacts from production of PV systems.

Environmental impacts from operation of PV systems

Operation of PV systems normally does not have any effect on environment. According to Goetzberger and Hoffmann (2005), PV system and electricity generated from them make an important contribution to the protection of the environment because they do not emit noise, solid waste, or gases that could harm the environment. Since PV systems do not generate emissions during operation, all their life cycle CO_2 emission is indirect ones which result from manufacturing process and is calculated by dividing the total amount of emissions generated during manufacturing of all needed components of the PV system (including possible replacements), by the total energy produced during their lifetime. In case of defects or wear-out of system components during operation, the damaged components have to be replaced with new ones. If damaged components are not repairable, they should be returned for recycling.

The PV system recommended for this cladding design consists of monocrystalline silicon. The lifetime of the panel is approximately 30 years. In order to minimize capital and running costs, it is proposed that PV panel is not connected to the grid and there is no inverter, but there is battery back up to be charged in days of high sun and discharged in days of lower sun. Using electricity as it is generated reduces transmission losses, and elimination the PV connection to the national grid makes the cladding module as a self powered module which does not need any connection to the building or to neighbouring modules. Total PV system efficiency including balance of system components is assumed to be 12%.

This chapter gives information surrounding main issues related to office building façade design, including façade elements U-Values, materials of glazed and non-glazed portions, ventilation system and lighting consideration. It also presents main factors when considering design of facades integrated PV, including PV efficiency, its costs and environmental impacts. Essentials necessary information in order to design a detailed PV cladding for offices is so far considered. The next chapter illustrates assumed office space for which the PV cladding is designed.

4. Case study office space

It is proposed to design the PV cladding for an assumed office module in an office building in London. This chapter presents the assumed office space and gives necessary information like its location, orientation, dimensions, occupancy and equipments. Building services, elements and conditions explained in this part dedicate to the office space after refurbishment. Tools used for modelling various aspects of the final design are also discussed here.

4.1. Assumed office space

The detailed PV cladding design is proposed for the south façade of an office building in London. Since the design desire to consider benefits of PV cladding, it is assumed that the south façade of the building is not shaded either by landforms or surrounding buildings.
In order to design the detailed PV cladding, it is proposed to first design the cladding unit for a representative module of an office space in the building, and then replicate it for the whole façade. So the number of floors is not taken into consideration in the design process, but the assumed office space dimension is important and is explained here.
The assumed office space facing south is supposed to have the potential of being naturally cross-ventilated. Obviously, there is a limit on the depth of office space that can be effectively naturally cross-ventilated and the rule of thumb for the maximum distance between the two facades is five times the floor-to-ceiling height (Irving et al 2005). This implies a narrow plan depth for the building. By considering this rule, the floor-to-ceiling height and distance between the two facades are assumed 2.70 m and 13.50 m respectively. As night cooling is proposed, no suspended ceiling is assumed, but there is a 0.50 m raised floor, so floor-to-floor height is 3.50 m.
The representative office module is proposed to be 6.30 m by 13.50 m by 3.50m (floor to floor height) and is 79.59 m^2 (without exterior walls), therefore the representative façade module is 6.00 m by 3.50 m. Like many office building in city centre, the occupancy density is considered to be 10 m^2 per person. So it provides working area for 8 occupants.
Two scenarios are proposed for the glazed area on south facade, the first one considers the maximum glazed area of 40% on south facing façade recommended by building regulation, part L (Anon 2006b), while the second scenario provides a fully glazed south façade (approximately 80% glazed area). It is possible to provide more than 40% glazed area if it is compensated in a better way like providing renewable energies (Chapter 3, p.10). In north facing façade, 40% glazed area is assumed. Figure 4.1, 4.2, 4.3 and 4.4 present assumed office space.

Figure 4.1: Plan of assumed office space

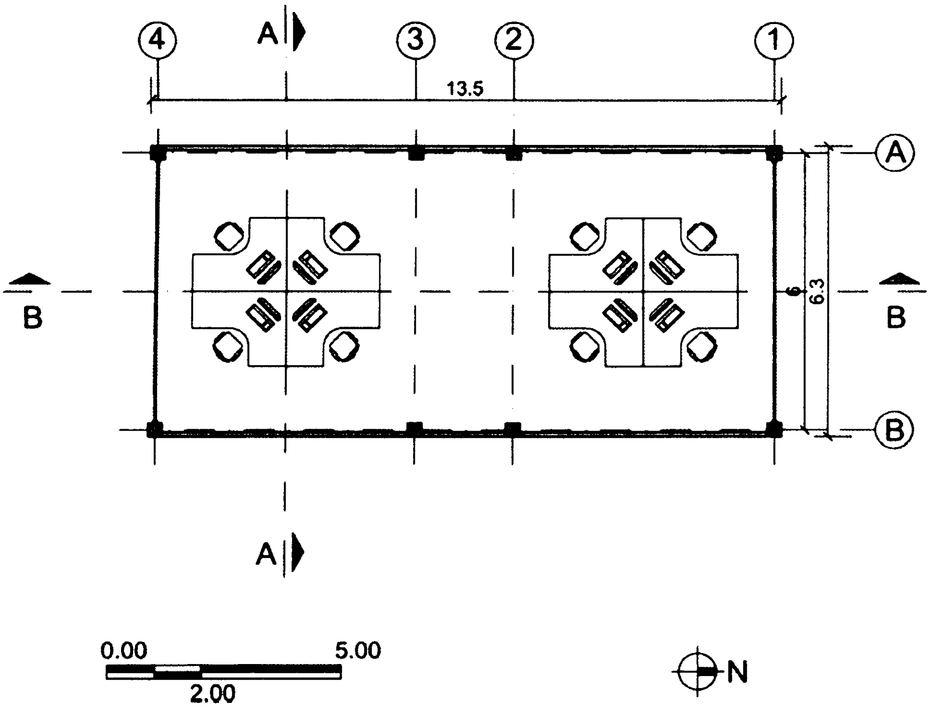


Figure 4.2: Section A-A of assumed office space

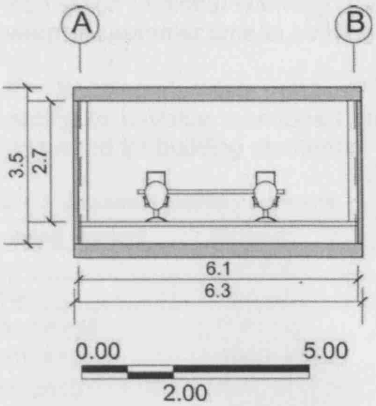


Figure 4.3: Section B-B of assumed office space (40% glazed area on south façade)

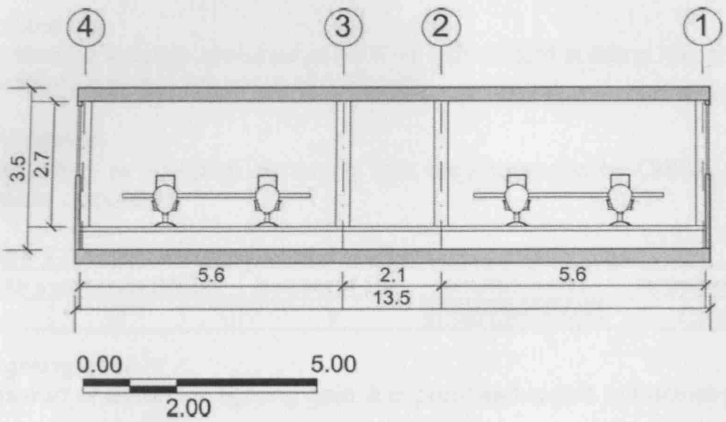
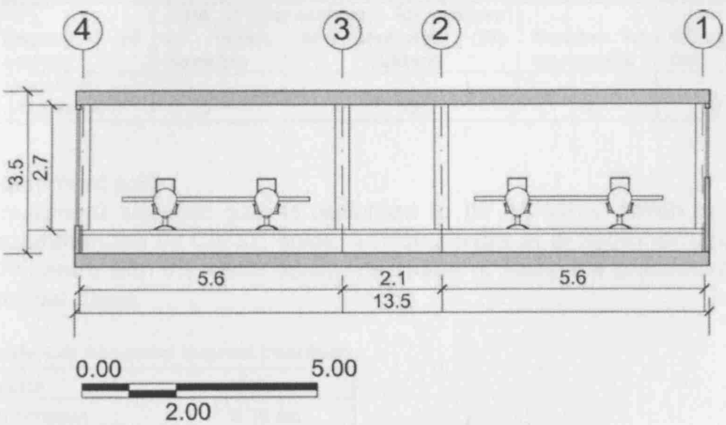


Figure 4.4: Section B-B of assumed office space (80% glazed area on south façade)



4.1.1. Weather

As the reason of global warming, the weather database file called UK_Kew_75_76_74, which has one the warmest summer time in London is used for simulations.

4.1.2. Building elements

According to U-Value mentioned previously (Chapter 3, p.10), the following materials and U-Values are assumed for building elements.

Table 4.1: Assumed building elements

Building element	Material	U-Value (W/(m^2.K))
Roof	Concrete	0.139
Floor	Concrete	0.107
External wall	Aluminium	0.106
Internal wall	Plaster board	0.287
Glazing(argon filled)	6mm 12mm 6mm	1.743
Frame	Aluminium	1.80

4.1.3. Internal conditions

In this section, assumptions made for internal gains, heating and cooling are presented.

Infiltration

Infiltration value is assumed to be 0.30 ach (a tight building has an infiltration value of 0.10 ach and an ordinary one has the value of 0.50 ach).

Ventilation

According to 10 l/(s.p) air supply rate recommended by CIBSE guide A (Chapter 2, p.6), ventilation rate is calculated.

Table 4.2: Ventilation rate of internal condition

Air supply rate (l/(s.p))	Number of stuff	Ventilation (l/s)	Volume of office	Ventilation (ach)
10	8	**80**	214.893	**1.34**

Lighting gain

Instead of assuming lighting gain, it is proposed to find out actual yearly lighting gains in the office.

Occupancy gains

Occupancy gains are calculated using the typical rates at which heat is given off by human beings in a moderate office work mentioned in CIBSE guide A (Humphreys et al 2006).

Table 4.3: Assumed occupancy gains

Degree of activity	Rate of heat emission for mixture of males and females (W) Sensible	Latent	Number of occupants	Office area (m^2)	Occupancy sensible gain (W/m^2)	Occupancy latent gain (W/m^2)
Moderate office work	75	55	8	79.59	**7.50**	**5.50**

Equipment gain

Equipment sensible gain is assumed to be 18 W/m^2 which is the same as benchmark allowance recommended by CIBSE guide A (Humphreys et al 2006) for equipment gain in a typical office in the city centre with the same occupancy pattern. Table 4.4 presents a summary of all assumptions for the internal gains.

Table 4.4: Assumed internal condition

Gain	Value
Infiltration	0.30 ach
Ventilation	1.34 ach
Lighting Gain	yearly W/m^2
Occupancy Sensible	7.50 W/m^2
Occupancy Latent	5.50 W/m^2
Equipment Sensible	18.00 W/m^2
Equipment Latent	0.00 W/m^2

4.1.4. Building service
No heating and cooling device is assumed, but it is assumed that there is a thermostat with the lower limit of 21°C and upper limit of 25°C. The occupancy schedule is 9:00-18:00; heating and cooling schedule is 8:00-18:00.

4.2. Modelling tools

The following software packages are used for simulations in the next chapter. A brief description of models and the purpose of using them are explained here.

4.2.1. Suntect (SQU1)
Suntect is a tool for the design of solar shading devices, but in this study it is used to find out monthly vertical shadow angles.

4.2.2. TAS[1] (EDSL)
Two models of assumed office space are generated in TAS (considering 40% and 80% glazed area). In order to minimize heat losses, office space is located in the middle of the first floor of a three-storey building (excluding the ground floor), so its floor and ceiling are common with the ground floor and second floor. Since it is located in the middle of the building, it only has two walls facing the exterior.

4.2.3. AGI32[2] (AGI32)
AGI32, a lighting package, is used to calculate daylight factor and to design electrical lighting. Daylight factor calculated in AGI32 is used in TAS to get yearly lighting gains. In order to make simulations, 3Dmodels are first drawn in AutoCAD. Assumptions made in AGI32 are explained in the next chapter.

4.2.4. AutoCAD[3] (Autodesk)
AutoCAD is used to draw 2D and 3D models of office space for simulations in TAS and AGI32.

In this chapter, assumed office space, assumptions made and software packages used for simulations are explained. In order to design the PV cladding, various components have to be designed. Next chapter first presents the design process of each component and then illustrates the final design.

1 - Thermal Analysis Software

2 - Advances Graphical Interface 32 bit format

3 - Computer Aided Design Software

5. Detailed facade design

This chapter explains experimental work of design process and presents the design of each component. It also illustrates the entire primary and final calculations and simulations, as well as their results, analysis and interpretation. One of the most important considerations is power available from each PV module, so this is designed first. Various factors for the PV panels need to be selected (i.e. its tilt, length, position and shape (louvered or not)), at the same time decision on glazed area is made. Different ventilation strategies are assessed. Eventually, final PV cladding design following its performance during the whole year as well as its energy consumption and internal conditions are considered.

5.1. Design of photovoltaic panel

Major advantage of PV as a renewable energy source is its ability to be integrated into buildings. Integration also allows the PV modules to be multi functional. As Jones (2000) describes, an array can, if properly incorporated, provide clean electricity, solar control, weather tightness and aesthetic appeal. Significant saving can be achieved if these multiple performance characteristics are exploited. Additionally, the advantages of daylight and solar gains need to be balanced against potential overheating and heat loss through glass. Following sub-sections present the design process of PV panel and glazed area.

5.1.1. Photovoltaic tilt

In order to design photovoltaic panel, first of all it is proposed to calculate its optimum tilt from horizontal in each month. As mentioned in appendix E, a tilt from horizontal equal to the latitude of the site minus approximately 30° has approximately the maximum total annual solar radiation in London. But in this section, based on hourly incident solar radiation averaged over all weather conditions, the optimum tilt of PV in each month is calculated.

Page and Lebens (1986) present daily incident solar radiation averaged over all weather conditions of a representative day in each month of a south facing facade with five different tilts (i.e. 90°, 67.5°, 45°, 22.5° and horizontal). So, based on the data available, monthly incident solar radiations on a south facing façade with these five tilts are calculated. Table 5.1 presents the summary of monthly incident solar radiation averaged over all weather conditions as well as the tilts by which the maximum monthly solar radiation is achieved. For details on calculations see appendix F.

Table 5.1: Incident solar radiation averaged over all weather conditions (kWh/m^2) (Page and Lebens 1986, p.116-120)

Month	South, Tilt: 90°	South, Tilt: 67.5°	South, Tilt: 45°	South, Tilt: 22.5°	South, Tilt: Horizontal
January	27.59	**30.02**	29.14	25.11	18.29
February	43.40	49.00	**49.28**	43.96	33.60
March	68.82	82.46	**87.42**	82.77	69.13
April	70.80	91.80	104.10	**106.20**	96.30
May	79.98	110.05	131.44	**140.12**	134.23
June	81.90	116.10	142.20	**155.40**	152.70
July	79.67	111.26	134.54	**145.39**	141.36
August	81.22	107.57	124.31	**128.65**	119.04
September	78.30	96.30	**104.40**	101.10	86.10
October	63.55	72.54	**73.47**	66.03	51.15
November	42.90	**46.50**	44.70	37.50	26.10
December	27.90	**29.45**	27.90	23.25	15.50

Therefore, in order to achieve maximum possible energy output, the angle of PV should be flexible changing. Table 5.2 illustrates monthly proposed PV tilts.

Table 5.2: Optimum tilts of south facing surface to achieve maximum solar radiation

Month	Maximum solar radiation averaged over all weather conditions (kWh/m^2)	Tilt
January	30.07	67.5°
February	49.28	45°
March	87.42	45°
April	106.20	22.5°
May	140.12	22.5°
June	155.40	22.5°
July	145.39	22.5°
August	128.65	22.5°
September	104.40	45°
October	73.47	45°
November	46.50	67.5°
December	29.45	67.5°

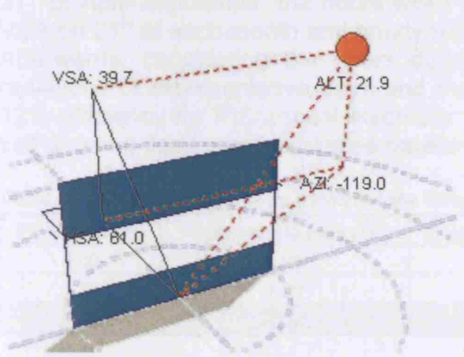
5.1.2. Photovoltaic length

In order to design PV panel, next step is to specify its optimum length. The more the PV surface area, the more the energy output is, but as mentioned before, shading affects PV energy output (Appendix E) and a degree of self-shading lowers the annual output. Actually, this study only considers the design of a PV cladding module, but when the cladding is designed it is replicated on other floors as well. In order to achieve the maximum annual energy output, PVs should not shade each other. So it is important to calculate the optimum PV length which provides the maximum annual energy output.

There are different approaches to calculate the optimum PV length. In this study two scenarios are proposed, first scenario considers no self-shading on PV at all, where as the second one proposes no self-shading during 6 hours per day (9:00-15:00). Calculation of this stage is only based on four representative days (March 21, June 21, September 21 and December 21), and yearly performance of the proposed PV lengths at this stage are analyzed afterwards.

Vertical shadow angle (VSA) is used to find out when PVs are shaded by each other. Figure 5.1 shows how VSA can be used to design optimum external shading for a south facing façade; the same strategy is used in this study to verify when PV self-shading occurs.

Figure 5.1: VSA on September 21 at 3:30pm (Suntect)



The VSAs of those four representative days are achieved form Suntect software (SQU1) and appendix G illustrates them. Based on VSA on those four representative days, and considering the two mentioned scenarios (no shading on PVs at all, and no shading during 6 hours/day), maximum PV lengths are calculated for each representative day. Table 5.3 and 5.4 illustrate maximum PV lengths to provide no self-shading at all and no self-shading during 6 hours/day respectively on each representative day. For more details see appendix H.

Table 5.3: Maximum lengths of PV to provide no self-shading on four representative days

Date	Tilt	Maximum length (m)
March-21	45	2.77
June-21	22.5	0.68
September-21	45	1.82
December-21	67.5	3.40

Table 5.4: Maximum lengths of PV to provide no self-shading during 6hours/day on four representative days

Date	Tilt	Maximum length (m)
March-21	45	2.77
June-21	22.5	1.21
September-21	45	2.70
December-21	67.5	3.40

As illustrated in above tables, maximum PV lengths proposed here are 0.68 m, 1.21 m, 1.82 m, 2.70 m, 2.77 m and 3.40 m. These PV lengths are calculated based on the result of one or two days, so it is necessary to find out if these PV lengths provide self-shading during all four representative days. Table 5.5 shows proposed maximum PV lengths and their self-shadings on all four representative days. As it shows no self-shading occurs when considering PVs 0.68 m long, where as considering PVs 1.21 m and 1.82 m long, self-shading occurs during June 21. PVs 2.70 m and 2.77 m long shade each other completely on June 21 and September 21, and PVs 3.40 m long shade each other completely on 21st of March, June and September. For more details see appendix I.

Table 5.5: Maximum PV lengths and consequent self-shadings on four representative days

Date	PV 0.68 m long	PV 1.21 m long	PV 1.82 m long	PV 2.70 m long	PV 2.77 m long	PV 3.40 m long
March-21	No self-shading	No self-shading	No self-shading	No self-shading	No self-shading	Completely shaded
June-21	No self-shading	Some self-shading	Completely shaded	Completely shaded	Completely shaded	Completely shaded
September-21	No self-shading	No self-shading	No self-shading	Completely shaded	Completely shaded	Completely shaded
December-21	No self-shading	No self-shading	No self-shading	No self-shading	No self-shading	No self-shading

Options in which PVs completely shade each others during one of four representative days are omitted. As illustrated in table 5.5, only PV length of 0.68 m, 1.21 m and 1.82 m are accepted at this stage. It is important to note that PVs 1.82 m long completely shade each others during June 21, but it is not omitted to compare its annual energy output with others. In order to compare annual energy output of these three options, 21st of each month is selected as the representative day of that month. Analysis shows that self-shading only occurs from April-September, so according to hourly VSA on 21st of April-September, the hours when PVs shade each other are calculated. Appendix J illustrates VSA on 21st of each month and hourly VSA on 21st of April-September.

Afterwards, considering the hours during which PV self-shading occurs, first daily incident solar radiations of representative days and then monthly solar radiation are calculated. Finally, assuming 12% efficiency for PV, annual electricity generated is calculated. Appendix K presents when exactly self-shading occurs and illustrates details on calculation of energy generated by each of three options.

Table 5.6: Photovoltaic energy output of the three different photovoltaic lengths

PV length (m)	Photovoltaic area (m^2)	Electricity generated by 12% efficient photovoltaic panel (kWh/yr)
0.68	4.08	536.77
1.21	7.26	887.63
1.82	**10.92**	**905.93**

As table 5.6 presents, PV 1.82 m long provides the maximum energy output. But as mentioned before, this option completely shades other PVs during June 21. So it is proposed to consider other options between PV length of 1.82 m and 1.21 m (i.e. PV length of 1.30 m, 1.40 m, 1.50 m, 1.60 m and 1.70 m). Calculation of energy output of these five options has the same procedure, but it is not presented because of its huge amount of data. Table 5.7 shows energy output of these PVs.

Table 5.7: Energy output of 8 different PV lengths

PV length (m)	PV area (m^2)	Energy generated by 12% efficient PV panel (kWh/yr)
0.68	4.08	536.77
1.21	7.26	887.63
1.30	7.80	928.94
1.40	8.40	987.84
1.50	9.00	1001.81
1.60	9.60	1050.59
1.70	10.20	993.83
1.82	10.92	905.93

Based on annual energy generated by different PV lengths and considering PV self-shading, the PV 1.60 m long is proposed as the optimum option. Appendix L presents details on calculation of energy generated by PV 1.60 m long. As it shows considering PV length of 1.60 m, self-shading occurs mostly during June 21. Table 5.8 presents its monthly and annual energy output.

Table 5.8: Electricity generated by a 9.60 m^2 (1.60 m*6 m) PV panel (12% efficiency)

Month	Tilt	Electricity generated (kWh)
January	67.5°	34.64
February	45°	56.77
March	45°	100.71
April	22.5°	113.08
May	22.5°	111.88
June	22.5°	88.51
July	22.5°	116.28
August	22.5°	136.32
September	45°	120.27
October	45°	84.64
November	67.5°	53.57
December	67.5°	33.93
Year	Various	**1050.59**

In order to design PV panels, optimum monthly PV tilts (22.5°, 45° and 67.5°) and length (1.60 m) are defined. But, annual internal energy consumption (heating, cooling and lighting) might be affected by different PV positions, so next design step is to investigate the optimum PV position as well as glazed area of the south façade.

5.1.3. Photovoltaic position and glazed area

To prevent overheating during summer, PV panels are supposed to control solar gains. Obviously, fixed devices, if suits summer time, would overly hinder winter gain benefits. By using different software packages an adjustable system is developed.

It is proposed to find out monthly optimum PV position, so different PV positions are analyzed to verify their impacts on monthly internal heating, cooling and lighting requirements, then PV position which result in the minimum monthly requirements is selected. The vertical distance between PVs is fixed (i.e. 3.50 m), and 6 PV positions are proposed to be analyzed. Also, two scenarios are previously assumed for glazed area (40% and 80%), so 6 different PV positions with two glazed areas (on overall 12 options) are analyzed to compare their impacts on monthly internal heating, cooling and lighting requirements. Table 5.9 presents PV positions relative to the raised floor. For more details see appendix M.

Table 5.9: Proposed PV positions relative to the raised floor

PV position	Vertical distance between top of the PV panel and raised floor (m)
1	4.60
2	4.10
3	3.60
4	3.10
5	2.60
6	2.10

As previously mentioned, different software packages, including TAS, AGI32 and AutoCAD are used for simulations. Assumed office is first simulated in TAS to analyze monthly internal energy requirements with different PV positions. Two models (40% and 80% glazed area on south facade) are made in TAS. Assumptions made for simulations in TAS are previously explained (Chapter 4, p.19). Following figures show 2D and 3D of one of the models in TAS.

Figure 5.2: 3D view of the model in TAS

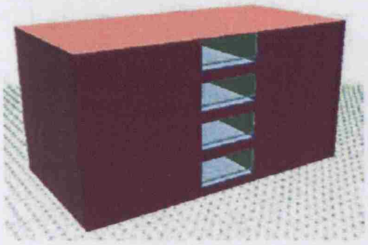
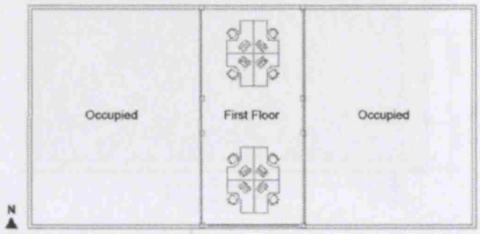


Figure 5.3: 2D view of the model in TAS



In order to simulate options in TAS, it is proposed to calculate yearly lighting gain first. By using TAS-Macro-Daylight availability, yearly lighting gain can be calculated for each scenario. But before calculating yearly lighting gain in TAS-Macro-Daylight availability, it is necessary to calculate daylight factor and maximum lighting gain (when no daylight is available) in lighting software, called AGI32.

Daylight factor
In order to calculate the daylight factor in AGI32, a 3Dmodel of each option is first made in AutoCAD. Daylight factor is calculated for 36 models (i.e. 6 (PV position) * 2 (glazed area) * 3 (different tilts)).

Figure 5.4: Sample of a 3D model in AutoCAD

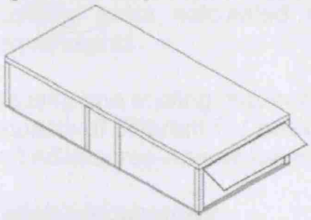


Table 5.10 shows the main properties applied to each surface in AGI32. At this stage no transparency is assumed for PV. Assumptions made in daylight parameters are presented in table 5.11.

Table 5.10: Surface properties in AGI32

Surface	Reflectance	Transparency
Ceiling	0.70	-
Floor	0.20	-
Wall	0.50	-
Glass	-	0.80
PV	0.20	-

Table 5.11: Daylight parameters in AGI32

Sky condition	Site location	Date	Time
Overcast sky	London (latitude: 51.65˚, longitude: 0.167˚)	21-Jun-06	12:00:00

Daylight factor of different models is calculated for the surface 0.70 m above floor level (i.e. desk level). Appendix N presents daylight factor for each options.
Moreover, electrical lighting is designed in AGI32 to calculate the maximum lighting gain when no daylight is available. Final lighting design proposes to use a twin 54 W T5 fluorescent luminaire and its total circuit is 944 W with lighting power density of just over 11.60 W/m^2. Since the total power of lighting equipment can be considered as going into the room, so the light power density equals the heat gain. Therefore, the maximum lighting heat gain is 11.60 W/m^2.

Appendix O compares electrical lighting design options. Additionally, there is no false ceiling so lighting equipments are included in a trunking system. Following figures illustrate final electrical lighting layout.

Figure 5.5: 3D view of lighting design in AGI32

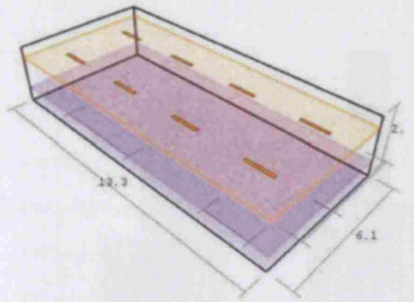
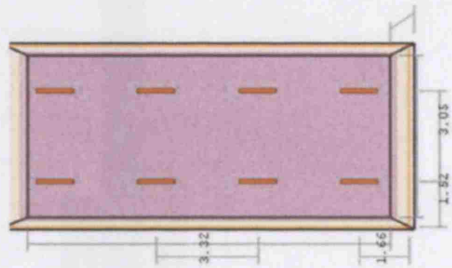


Figure 5.6: Plan of lighting design in AGI32



TAS-Macros-Daylight availability

Based on daylight factors and maximum lighting gain calculated in AGI32, yearly lighting gain of each option is calculated in TAS-Macros-Daylight availability. Table 5.12 illustrates the input data and assumptions made.

Table 5.12: Assumptions in TAS-Macros-Daylight availability

Daylight factor	Minimum lux level	Minimum lighting gain	Maximum lux level	Maximum lighting gain	Time period
As calculated in AGI32	0 lx	0 W/m^2	500 lx	11.60 W/m^2	Weekdays 9:00-18:00

Lighting gains calculated here are used for simulations in TAS to find out monthly energy requirements.

Heating and cooling requirements

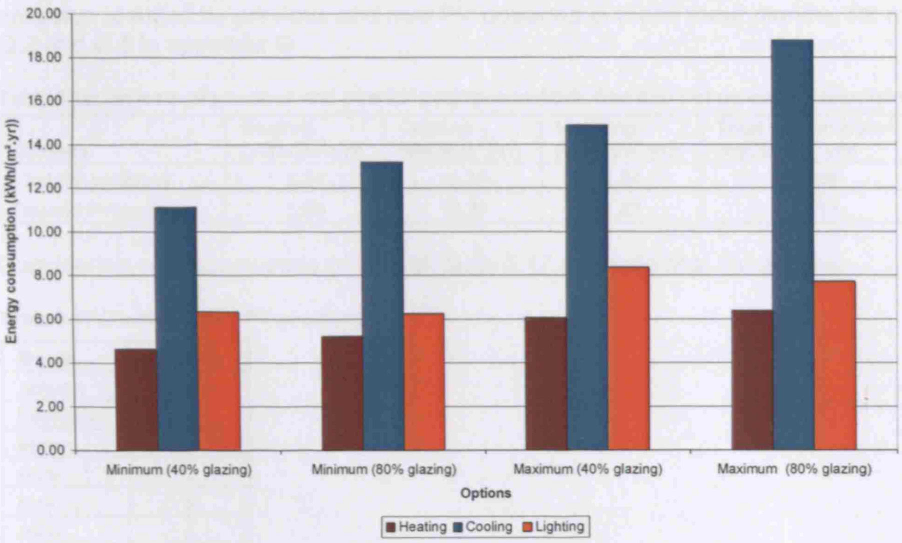
Impacts of different PV positions and glazed area on monthly heating and cooling loads are analyzed in TAS-Macros-Annual loads. The loads in this part do not present lighting loads.

Lighting requirement

As previously mentioned, total power of the lighting equipment can be considered as going into the room, so the light power density equals the heat gain. Therefore, monthly lighting consumption equals monthly lighting heat gain. It is proposed to calculate impacts of all options on monthly lighting heat gain and consequently monthly lighting consumption based on their hourly lighting heat gains produced in TAS-Macros-Daylight availability.

Appendix P presents impacts of all options on monthly heating, cooling and lighting requirements and CO_2 emission. In order to find out monthly optimum PV position, two PV positions (with 40% and 80% glazed area) which result in the minimum total energy requirements and CO_2 emission are selected for each month. Also, two PV positions which result in the maximum total energy requirements and CO_2 emission are selected to compare their energy requirements with that of the options which result in minimum loads. Chart 5.1 shows options which results in the minimum and maximum annual energy requirements and CO_2 emission. For details on monthly PV positions and internal energy requirements of these options see appendix Q.

Chart 5.1: Minimum and maximum internal energy requirements resulted by different PV positions and glazed area



As chart 5.1 shows, both energy and CO_2 emission can be saved by implementing an optimum monthly PV position. In order to select the optimum PV position and glazed area, the options which result in the minimum annual energy requirements and CO_2 emission are compared. Table 5.13 shows that there is not significant difference between their annual requirements and CO_2 emission (for more detail see tables Q.1 and Q.2 in appendix Q); considering that nowadays most clients prefer fully glazed facades, it is proposed to design the PV cladding with 80% glazed area on the south façade.

Table 5.13: Minimum annual energy requirements and CO_2 emission resulted by two options

Options	Heating (kWh/(m^2.yr))	Cooling (kWh/(m^2.yr))	Lighting (kWh/(m^2.yr))	Total CO_2 emission (kgCO_2/(m^2.yr))
Minimum (40% glazing)	4.63	11.12	6.34	9.95
Minimum (80% glazing)	5.21	13.20	6.24	11.09

Table 5.14 shows monthly PV positions of the option which results in minimum annual consumption.

Table 5.14: Monthly PV positions

Month	Position
January	2
February	2
March	2
April	1
May	5
June	5
July	5
August	5
September	6
October	1
November	2
December	2

It might be a bit difficult for occupants to have control over changes in PV positions in April, September and October. So it is proposed to investigate other available optimum positions in April, September and October as close as possible to that of their adjacent months, and then compare their impact on energy requirements. Table 5.15 illustrates new proposed positions.

Table 5.15: Proposed positions in April, September and October

Month	Position
April	2
September	5
October	2

As table 5.16 illustrates, there is not significant difference between annual consumption and CO_2 emission resulted by previous and new PV positions in these three months, for more detail see tables Q.2 and Q.5 in appendix Q.

Table 5.16: Impacts of previous and new PV positions in April, Sep and Oct on energy requirements and CO_2 emission

Options	Heating ($kWh/(m^2.yr)$)	Cooling ($kWh/(m^2.yr)$)	Lighting ($kWh/(m^2.yr)$)	Total CO_2 emission ($kgCO_2/(m^2.yr)$)
First PV positions	5.21	13.20	6.24	11.09
Second PV positions	5.03	13.29	6.27	11.13

Considering occupancy ease of control, table 5.17 presents final PV potions.

Table 5.17: Final monthly PV positions

Month	Position
January	2
February	2
March	2
April	2
May	5
June	5
July	5
August	5
September	5
October	2
November	2
December	2

Appendix R presents proposed monthly tilts, length and positions of PV panel.

5.1.4. Photovoltaic panel, louvred or not

PV tilts, length and positions are optimized so far, but only one PV panel 1.60 m long is considered. It is proposed to analyze performance of louvred PVs with the same total length. As an illustration, following figures show previous PV shape and proposed louvred one in February and September.

Figure 5.7: February, one PV panel 1.60 m long

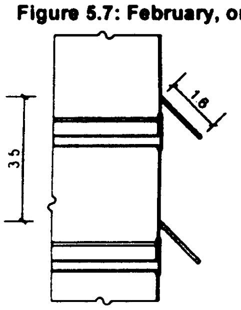


Figure 5.8: September, one PV panel 1.60 m long

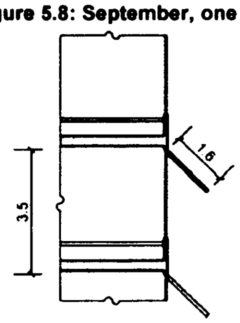


Figure 5.9: February, 3 PV panels 0.53 m long

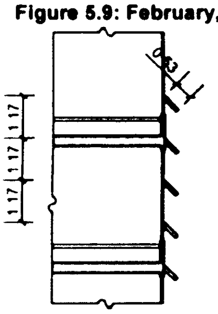
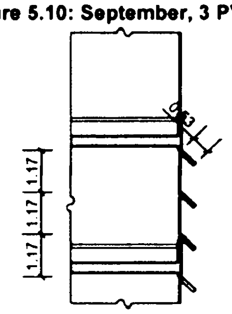


Figure 5.10: September, 3 PV panels 0.53 m long



In order to analyze different PV panel shapes, it is proposed to consider items including; PV output, its effect on annual energy requirements, aesthetic, maintenance and structure of PV panel itself. There is no difference between energy output of louvred PV (3 panels of 0.53 m long) and that of a PV panel 1.60 m long. For details on energy output of louvred PV see appendix S.
The procedure to compare internal energy requirements of these two PV panels is the same as before. But in order to make the comparison as accurate as possible, transparency value of 0.50 is considered for PV both in TAS (to calculate heating and cooling requirements) and in AGI32 (to calculate daylight factor and lighting consumption). Appendix T shows daylight factor of both options calculated at this stage.
As table 5.18 shows, considering PV transparency increases the cooling requirement of PV panel (1.60 m long) by 2.78 kWh/(m^2.yr), and decreases its heating and lighting requirement by 0.24 and 0.23 kWh/(m^2.yr) respectively.

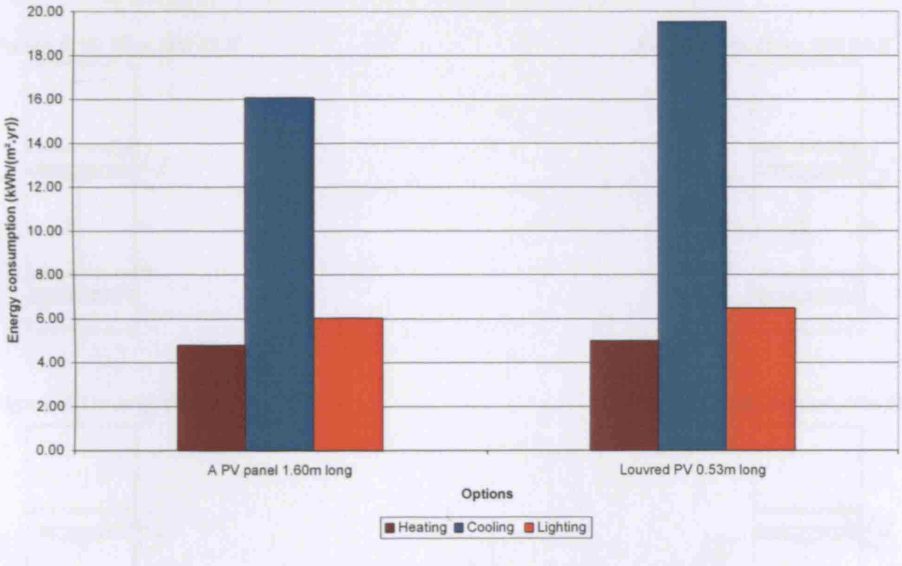
Table 5.18: PV transparency impacts on energy requirement and CO_2 emission when installing a PV panel 1.60 m long

Options	Heating (kWh/(m^2.yr))	Cooling (kWh/(m^2.yr))	Lighting (kWh/(m^2.yr))	Total CO_2 emission (kgCO_2/(m^2.yr))*
A PV panel 1.60 m long	5.03	13.29	6.27	11.13
A PV panel 1.60 m long (0.50 transparency for PV)	4.79	16.07	6.04	12.41

* Gas CO_2 emission factors: 0.19 kgCO_2/kWh, Electricity CO_2 emission factors: 0.52 kgCO_2/kWh (Anon, 2003a)

Following chart presents impacts of two proposed PV shapes, (i.e. a 1.60 m panel and 3 panels 0.53 m long) on internal energy requirements.

Chart 5.2: Impacts of PV shapes on internal energy requirements



As table 5.19 shows using louvred PV panels augments heating, cooling and lighting requirements by 0.21, 3.46 and 0.45 kWh/(m^2.yr) respectively.

Table 5.19: Impacts of PV panel shape (louvred or not) on annual energy requirement and CO_2 emission

Options	Heating (kWh/(m^2.yr))	Cooling (kWh/(m^2.yr))	Lighting (kWh/(m^2.yr))	Total CO_2 emission (kgCO_2/(m^2.yr))*
A PV panel 1.60 m long	4.79	16.07	6.04	12.41
Louvred PV 0.53m long	5.00	19.53	6.49	14.48

* Gas CO_2 emission factors: 0.19 kgCO_2/kWh, Electricity CO_2 emission factors: 0.52 kgCO_2/kWh (Anon, 2003a)

Due to ease of maintenance, structural and aesthetic characteristic of installing PV panels 0.53 m long instead of a 1.60 m one, this increase in amount of energy requirement is considered as negligible and louvred PV panels are proposed. Following figures present final proposed tilts, length, positions and shape of PV panels in each month.

Figure 5.11: January, tilt: 67.5˚

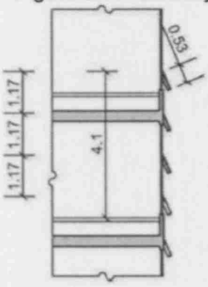


Figure 5.12: February, tilt: 45˚

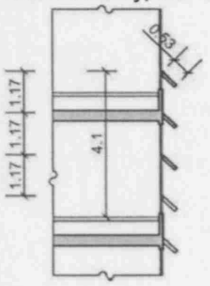


Figure 5.13: March, tilt: 45˚

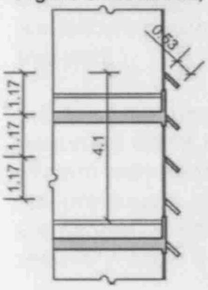


Figure 5.14: April, tilt: 22.5˚

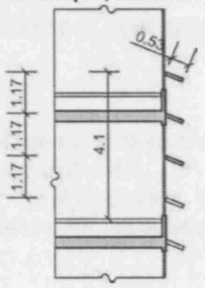


Figure 5.15: May, tilt: 22.5˚

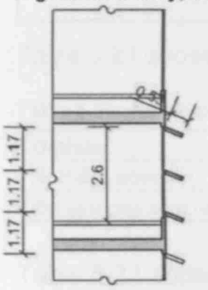


Figure 5.16: June, tilt: 22.5˚

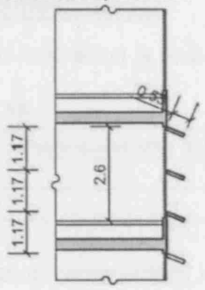


Figure 5.17: July, tilt: 22.5˚

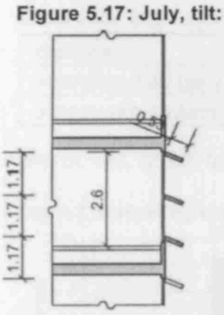


Figure 5.18: August, tilt: 22.5˚

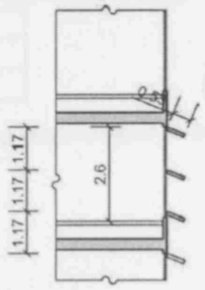


Figure 5.19: September, tilt: 45˚

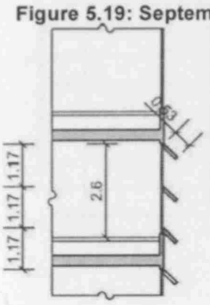


Figure 5.20: October, tilt: 45˚

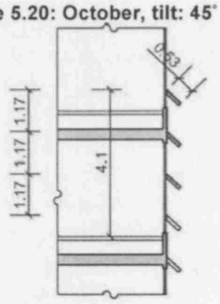


Figure 5.21: November, tilt: 67.5˚

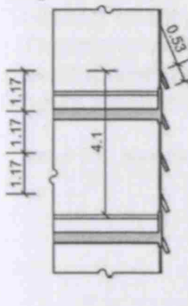
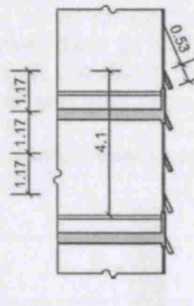


Figure 5.22: December, tilt: 67.5˚



5.2. Design of ventilation strategy

As following sub-section explains ventilation strategy with and without heat recovery is assessed in this part.

5.2.1. Heat recovery

Assumed office space is simulated in TAS to investigate advantages and disadvantages of ventilation system with heat recovery. Following assumptions are made in simulations.

As previously mentioned (Chapter 3, p.12) the only proper heat recovery device is plate heat exchanger which is 70% efficient, so considering 70% efficiency for ventilation system with heat recovery, table 5.20 shows ventilation rate assumed in TAS.

Table 5.20: Assumptions about ventilation rate of mechanical ventilation system with heat recovery in TAS

Air supply rate (l/s.p)	Number of stuff	Volume of office	Ventilation (ach)
3	8	214.893	0.40

Table 5.21 shows that office is assumed as tight as possible and infiltration is reduced to 0.10 ach.

Table 5.21: Assumptions about infiltration, ventilation and thermostat in TAS

Options	Infiltration (ach)	Ventilation rate (ach)	Thermostat with lower limit (˚C)
No heat recovery	0.10	1.34	21
Considering heat recovery	0.10	0.40	21

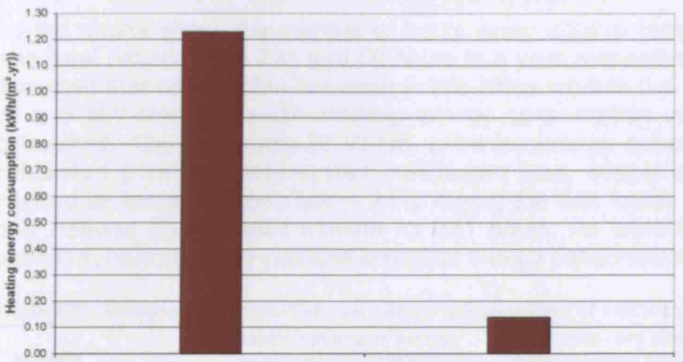
Table 5.22 shows that by considering 0.10 ach infiltration, heating requirement is decreased by 3.77 kWh/(m^2.yr), but cooling requirement is increased by 3.63 kWh/(m^2.yr).

Table 5.22: Impacts of decreased infiltration on heating and cooling requirement (louvred PV)

Options	Heating (kWh/(m^2.yr))	Cooling (kWh/(m^2.yr))
Infiltration 0.30 (ach)	5.00	19.53
Infiltration 0.10 (ach)	1.23	23.16

Moreover, chart 5.3 shows that heat recovery decreases heating requirement to 0.14 kWh/(m^2.yr).

Chart 5.3: Heating energy requirement with and without heat recovery



In order to omit entirely the need for central heating, it is proposed to assess internal condition and heating energy requirement with and without heat recovery, when no central heating is provided. Therefore, number of hours when internal temperature is lower than 21°C is calculated, and then heating energy requirements of both options are analyzed. Chart 5.4 and 5.5 present the number of hours when internal temperature is lower than 21°C, without and with heat recovery.

Chart 5.4: Number of hours when internal temperature is lower than 21 °C (without heat recovery)

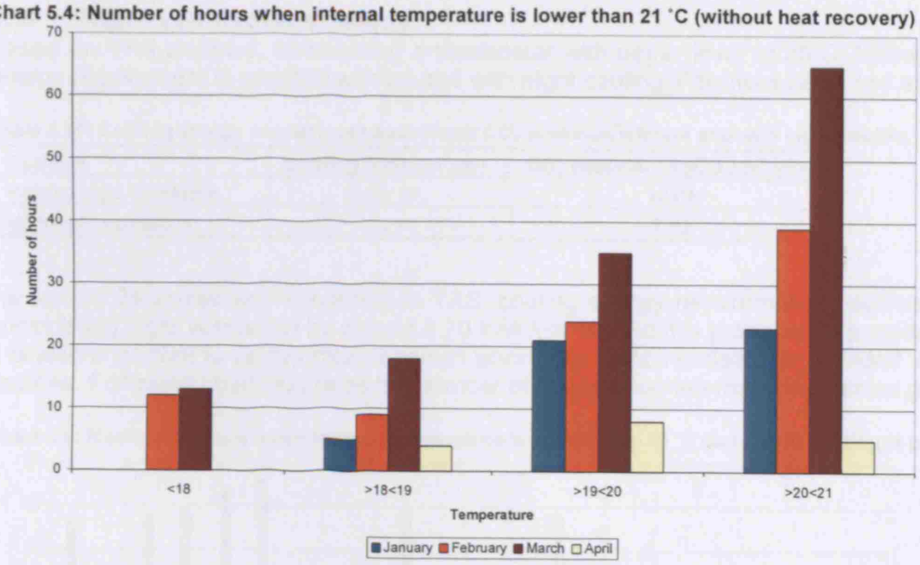
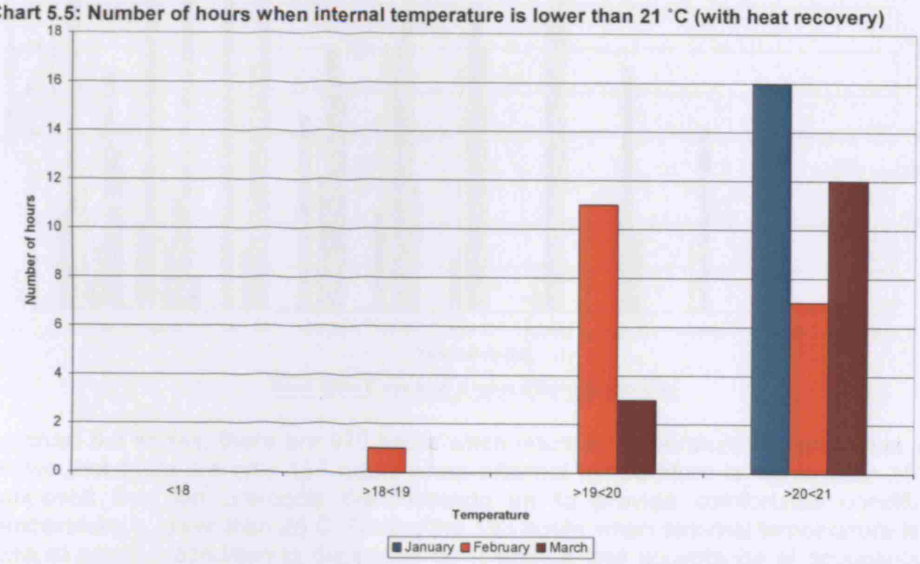


Chart 5.5: Number of hours when internal temperature is lower than 21 °C (with heat recovery)



As the charts show, the number of hours when internal temperature is lower than 21°C without and with heat recovery are 281 and 50 hours in a year respectively. If no central heating is provided, it is assumed that comfortable condition in this office module (i.e. 79.59 m^2) during winter time is provided by a 3 kW electric heater. Heating energy consumption of electrical heater for both systems are calculated. Also, assuming 27 W fan, extra fan energy consumption when heat recovery is in use is calculated (heat recovery system needs two fans, supply and extract), it is important to note that internal temperature goes below 21°C during the first fourth month of the year, and heat recovery is only needed during these months for 281 hours. As table 5.23 shows, when no central heating is provided, heat recovery reduces electrical energy consumption by around 81%.

Table 5.23: Maximum estimated annual energy consumption of electrical heater (without and with heat recovery)

System	Electrical heater energy consumption (kWh/yr)	Heat recovery energy consumption (kWh/yr)	Heating and heat recovery energy consumption (kWh/(m^2.yr))
Without heat recovery	843	-	10.59
With heat recovery	150	7.59	1.98

If occupants are prepared to accept just 50 hours in a year with temperature below 21˚C (e.g. by wearing more clothes), then no heating is required. If this is not the case, considering the benefits of omitting central heating which is explained in the next chapter, it is proposed to provide comfortable condition by electrical heater.

5.3. Night ventilation strategy

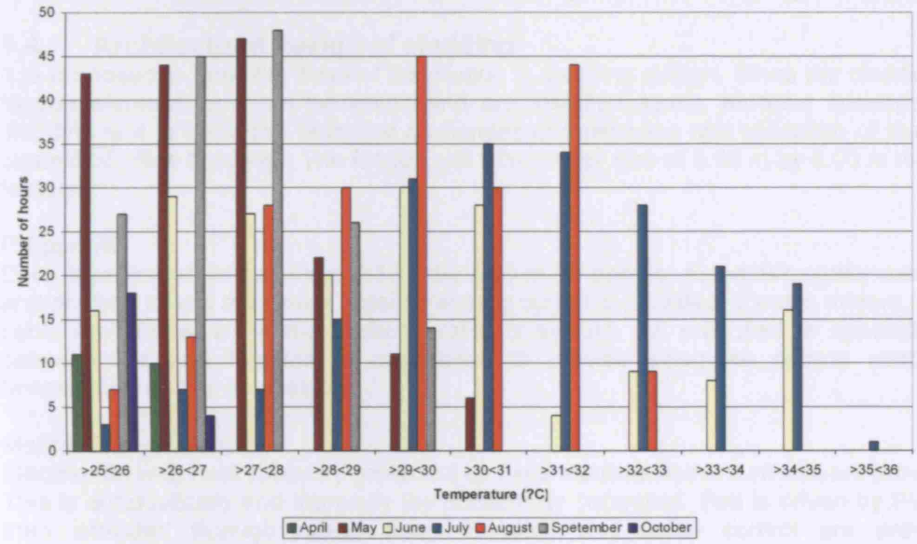
Based on TAS analysis, considering a thermostat with upper level of 25˚C, following annual cooling energy requirement is resulted without and with night cooling. For more detail see appendix U.

Table 5.24: Cooling energy requirement and related CO_2 emission without and with night cooling

Options	Cooling (kWh/(m^2.yr))	CO_2 emission (kgCO_2/(m^2.yr))
Without night ventilation	23.16	12.04
With night ventilation	14.47	7.52

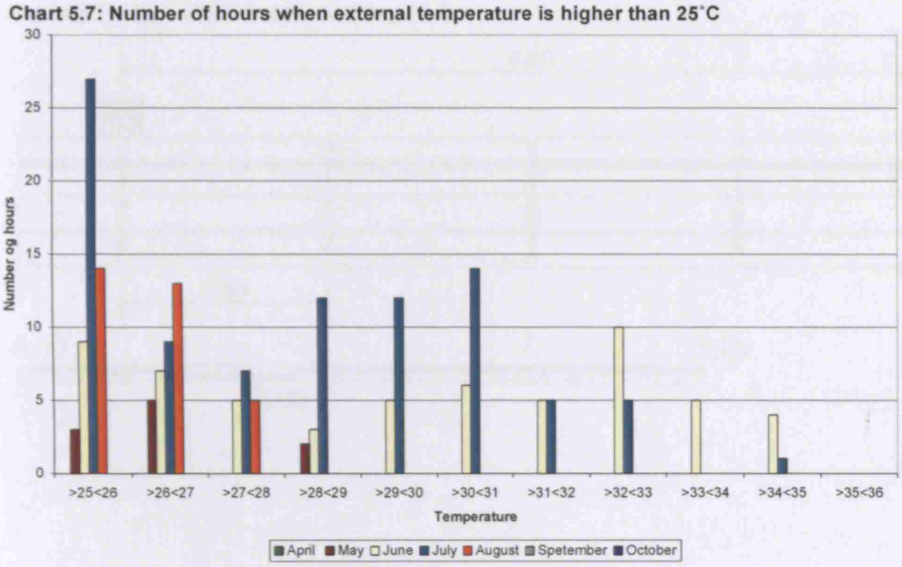
As table 5.24 shows and according to TAS, cooling energy requirement is decreased as a result of considering night ventilation by around 8.70 kWh/(m^2.yr). So it is proposed to provide night cooling, but it is also important to verify office condition when only night ventilation is provided without any cooling devices. Following chart illustrates the number of hours when internal temperature goes above 25 ˚C.

Chart 5.6: Number of hours when internal temperature is higher than 25 ˚C (only night cooling is provided)



As chart 5.6 shows, there are 970 hours when internal temperature is higher than 25˚C, but chart 5.7 shows that there are only 193 hours when external temperature is higher than 25˚C. Therefore, it is supposed that fan pre-cools the incoming air to provide comfortable condition when external temperature is lower than 25˚C. During the 193 hours when external temperature is higher than 25˚C, internal comfort condition is depended on tolerance and acceptance of occupants. If occupants are able to put up with this (e.g. less clothes) then no cooling is required. But if this is not the case, it is proposed to provide higher fan speed on hot days, so this extra air movement can provide comfort. Ventilation consumption to provide adequate fresh air (i.e. 80 l/s) is calculated based on fan consumption on its highest speed (i.e. 27 W when supplying 203 l/s) (Appendix C), so providing higher fan speed does not increase ventilation energy consumption.

Chart 5.7: Number of hours when external temperature is higher than 25˚C



5.4. Architectural design of cladding

It is proposed to consider ease of installation in cladding design. Since the cladding is modular all the façade elements are pre-fabricated and are installed easily. Modular concept is adopted for the cladding unit to solve the technical challenges of integration and operation of the cladding in a wider context of office buildings. The façade unit with overall size of 3.50 m by 6.00 m has the following main features:

PV panels

Each façade module has three 0.53 m by 6.00 m PV panels. Automatic and/or manual angular rotation and position to suit maximum possible energy output is provided. Electric motors, gearboxes and drive cable are concealed in the mullion profile of system. As proposed in appendix E, a 0.20 m gap between PV and facades is considered to provide adequate natural ventilation to keep PV temperature as low as possible.

Mechanical ventilation

Electric fan with heat recovery protected by fixed external aluminium louvers provides 80 l/s fresh air. This is automatically and manually (by occupants) controlled. Fan is driven by PV power. Fresh air is then provided through raised floor. Filtration and noise control are provided according to recommendations explained before (Chapter 2, p.7).

Window sections

Window has separate opening elements at different levels.

Upper section (0.60 m by 5.60 m, including frame) close to the ceiling acts as a secure night ventilator in summer. Central section (1.00 m by 5.60 m, including frame) provides view to outside, and is openable for maintenance. Lower section (0.90 m by 5.60 m, including frame) just above sill height is a vent to provide night cooling and comfort cooling in peak summer daytime conditions.

Internal blind for upper and central window to provide occupants control of glare

Obviously, control of various elements is vital to reduce unwanted solar gain, provide daylight and night cooling. It is proposed to control fan and PV elements by means of a local intelligent controller which operates either in a stand alone mode or by the building environmental management system (BEMS). However, it is possible to have all these elements to be controlled manually by occupants, which has its own advantages and disadvantages. It is also assumed that window openings are not motorized and can be manually controlled to minimize the cost of facade. The following figures illustrate final design of PV cladding module.

Figure 5.23: Plan of detailed PV cladding design

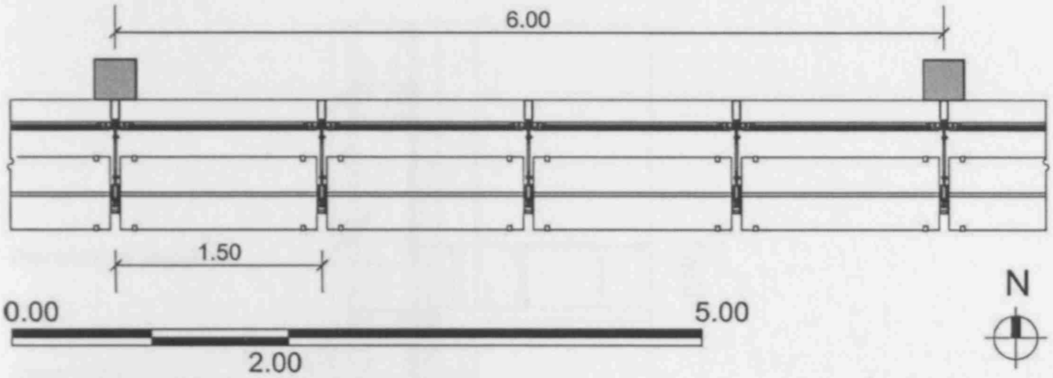


Figure 5.24: Details of PV cladding design in plan

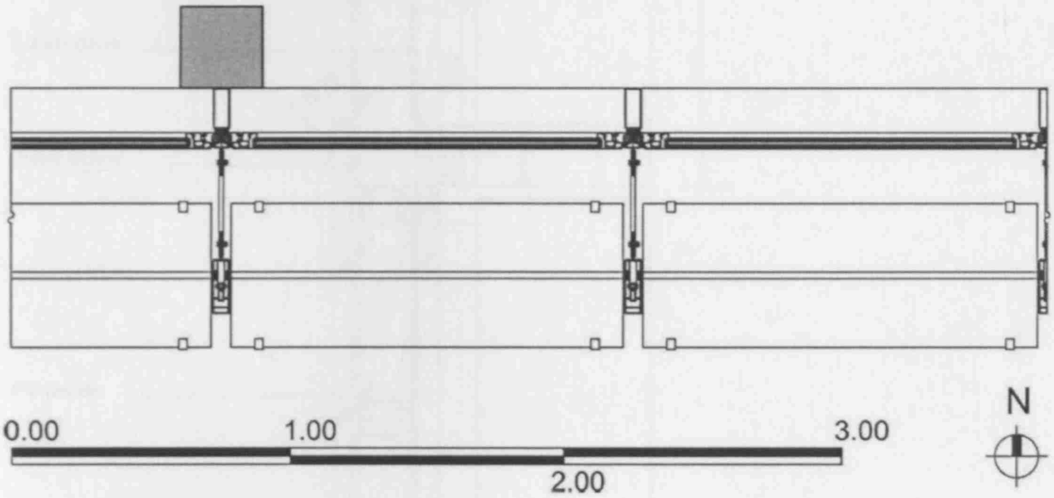


Figure 5.25: Section of PV cladding design

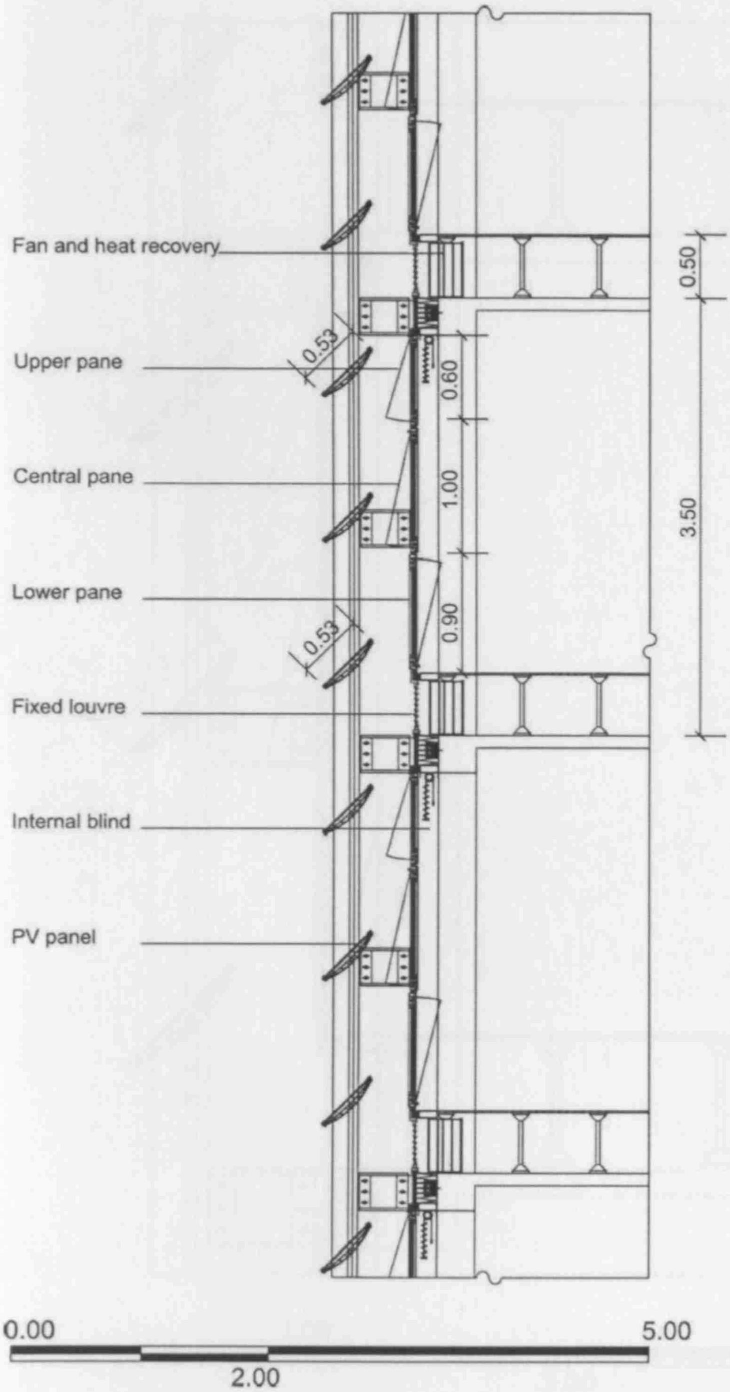


Figure 5.26: Details of PV cladding design in section

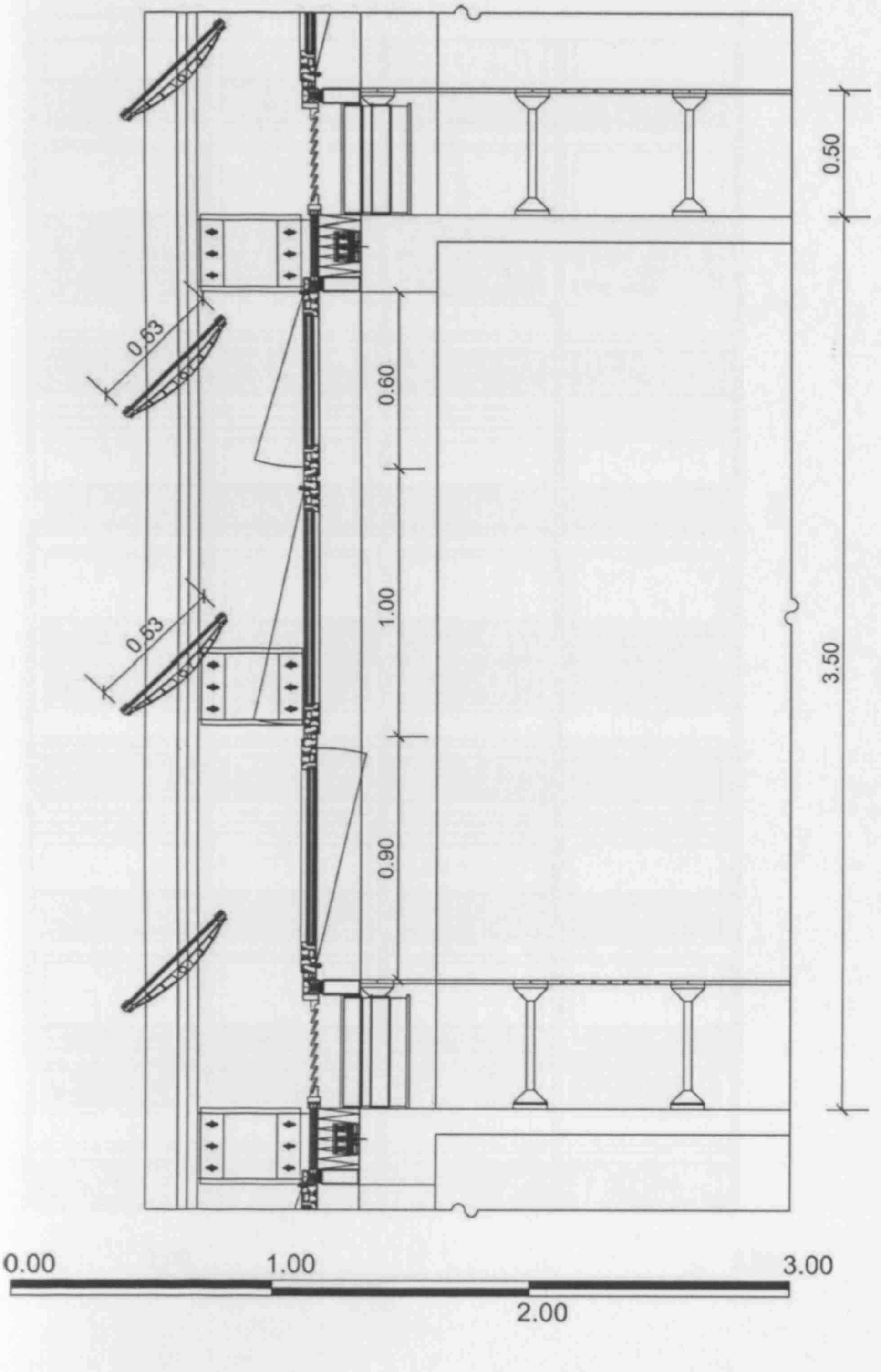


Figure 5.27: Elevation of PV cladding design

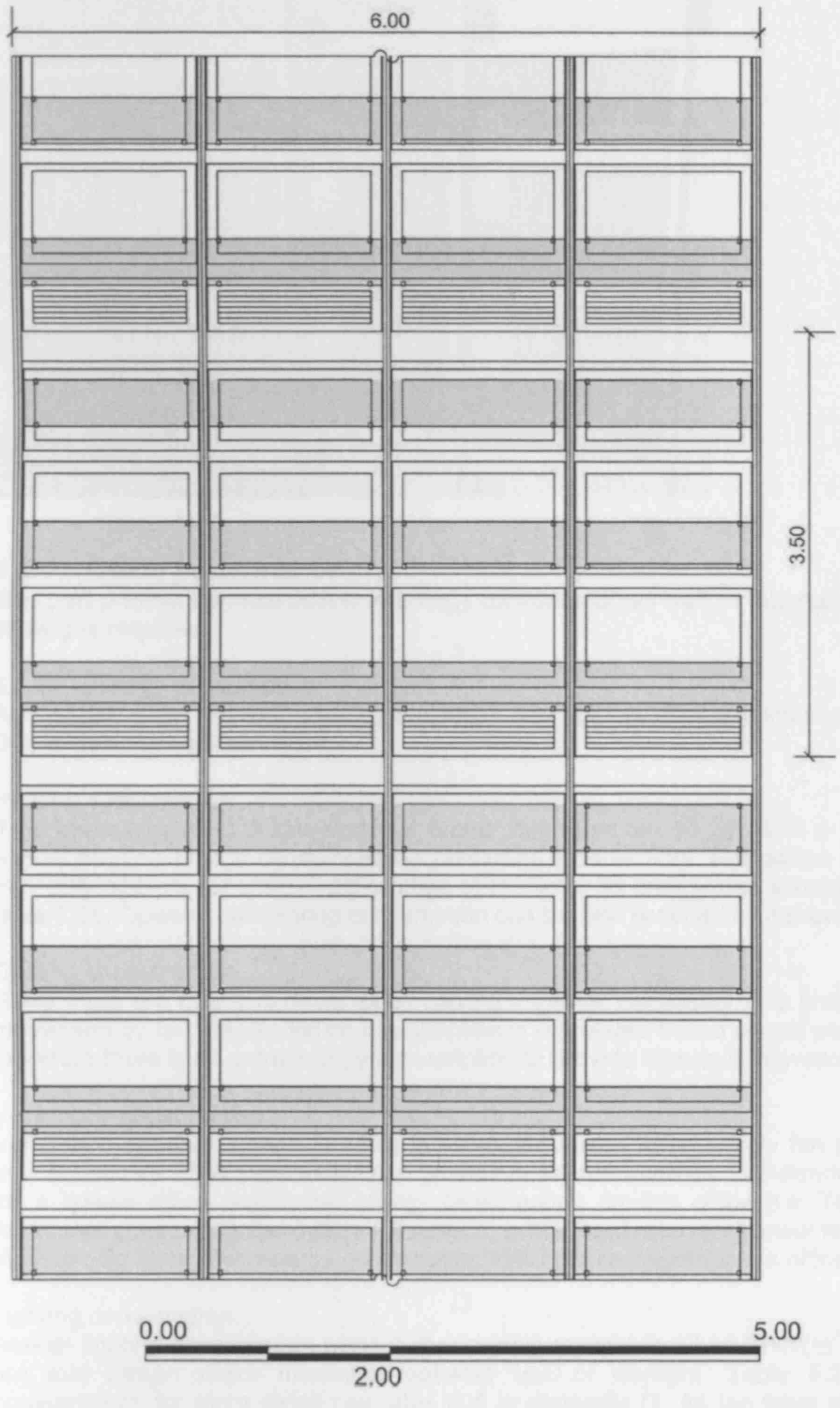
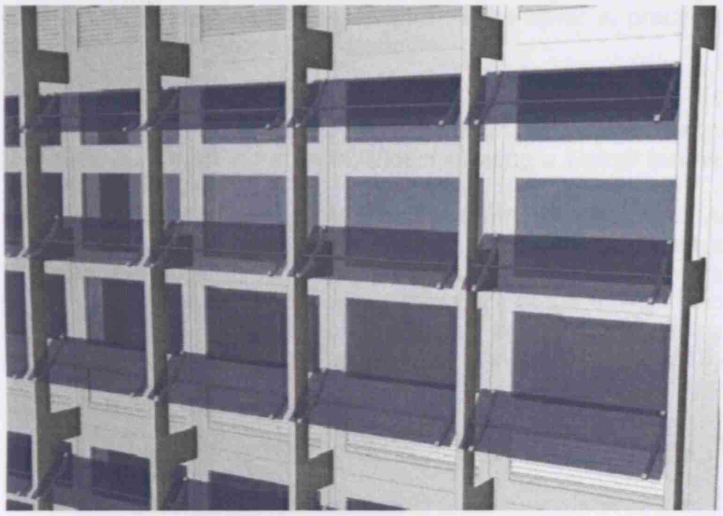


Figure 5.28: Image of PV cladding design



5.5. Office performance

This part presents annual delivered energy consumption as well as internal conditions when heating or cooling is required.

5.5.1. Energy consumption

Annual delivered heating, cooling, ventilation and lighting energy consumption as well as associated CO_2 emissions are calculated.

Heating consumption

If occupants use the 3 kW electrical heater during whole 50 hours in a year, estimated maximum annual heating energy consumption is presented in table 5.25. But, as the heater has a thermostat, it may only operate for a small percentage of the time, so energy use should be less than calculated in table 5.25. Operational heating consumption can be also reduced by behavioural policies in the office.

Cooling consumption

Since there are only 193 hours when cooling might be necessary, it is proposed to provide higher air movement by fan. As ventilation consumption is calculated based on fan wattage on its highest speed, therefore there is no extra energy consumption to provide higher air movement for cooling.

Ventilation consumption

Ventilation energy demand in office is estimated based upon supply fan energy consumption which only consumes 27 W (Appendix C) to provide adequate fresh air. Considering 2340 operating hours/yr for a typical office, ventilation energy consumption for this office (i.e. 79.59 m^2) is 63.18 kWh/yr. Additionally, as calculated before (Chapter 5, p.32), heat recovery consumes 7.59 kWh/yr in this office module. So ventilation energy consumption with heat recovery for this office module is 70.77 kWh/yr.

Lighting consumption

Annual lighting consumption without considering daylight is 27.14 kWh/(m^2.yr) ((11.60*9*5*52)/1000), but this design make maximum possible use of daylight. Table 5.25 shows annual lighting consumption, for more detail see table Q.5 in appendix Q. As the table shows, almost 70% energy required for lighting can be saved when considering daylight in electrical lighting design. However, this saving is only achieved if good lighting controls as well as educating occupants are provided.

Table 5.25: Annual energy consumption and CO_2 emission

	Energy consumption (kWh/(m^2.yr))	CO_2 emission (kgCO_2/(m^2.yr))
Heating	1.88 (150/79.59)	0.98
Cooling	-	-
Ventilation	0.88 (70.77/79.59)	0.46
Lighting	6.27	3.26
Total	9.03	4.70

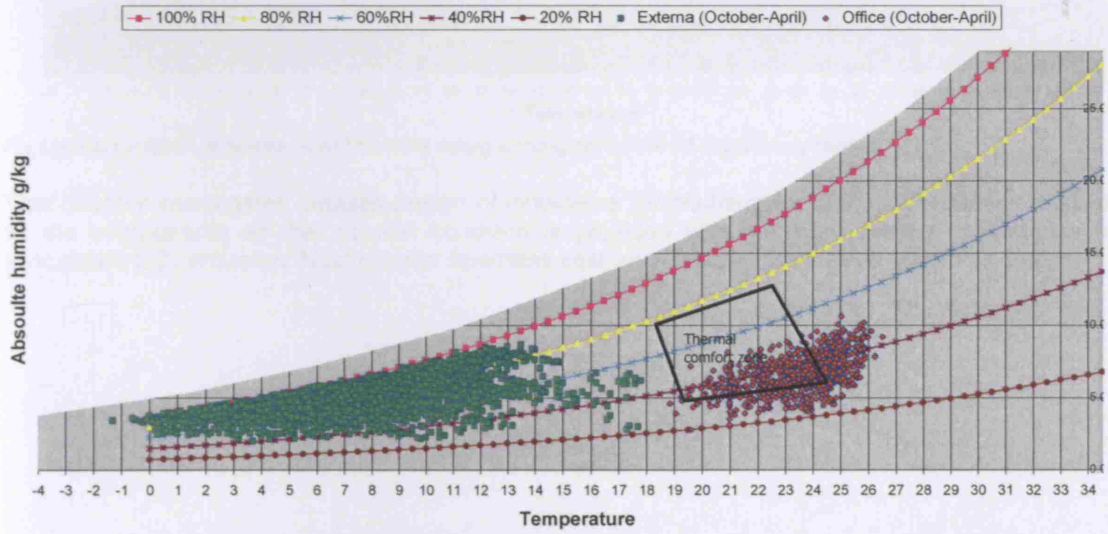
Parts of office energy consumption is provided by PV so annual energy consumption and associated CO_2 emission presented in table 5.25 will be lower in practice, next chapter presents actual energy consumption and related CO_2 emission.

5.5.2. Comfort condition

Thermal comfort zone in the following charts is limited in a narrow black rectangular, this zone is thermally comfortable for an individual wearing a typical business suit (Clo value of 1.0) and with an activity level of 1 Met.

Chart 5.8 shows office internal condition during October-April. As mentioned before, internal condition is depended on occupants' acceptance; if they are prepared to accept just 50 hours in a year with temperature below 21˚C, then internal conditions is comfortable during heating period. However, due to high internal gain in this office, there are hours in April and October that internal temperature is higher that 25˚C, but external temperature during these months is lower than 25˚C, so it is expected that comfort condition will be provided by pre-cool air supplied by fan.

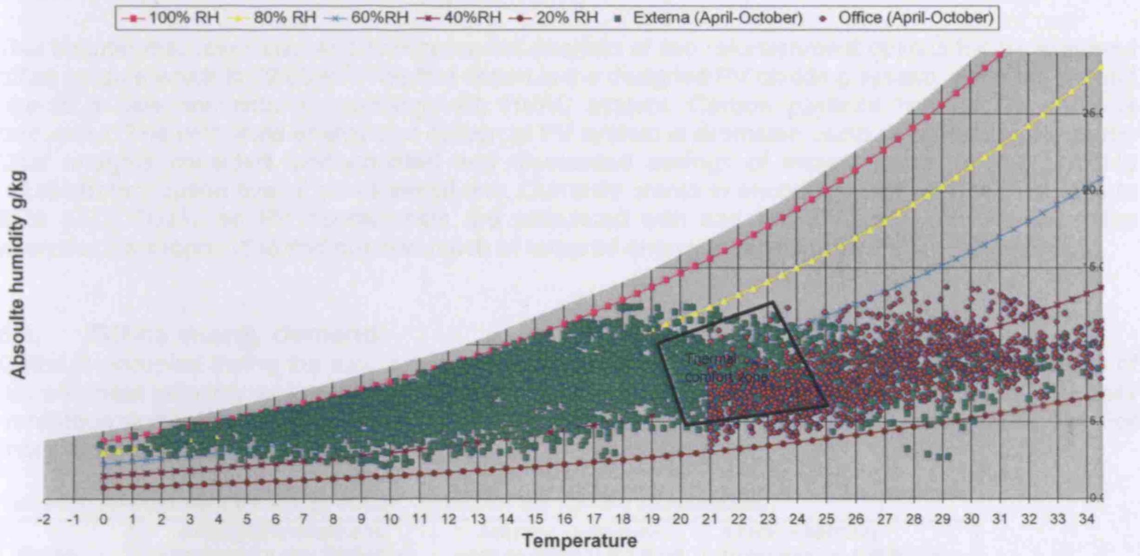
Chart 5.8: External and internal condition from October to April



For internal condition, temperature and humidity during working days (9:00-18-00) are only plotted.

Chart 5.9 shows office internal condition during April-October. As it shows there are a number of hours when internal condition is not comfortable, but by supplying pre-cooled air by fan, it is found that internal condition is not comfortable only when the external is also uncomfortable, so the internal condition will be more comfortable than that of presented in the following chart. Also it is expected that providing higher fan speed can provide comfortable condition when the external is uncomfortable, however internal condition is depended on occupants' tolerance and perception.

Chart 5.9: External and internal condition from April to October



For internal condition, temperature and humidity during working days (9:00-18-00) are only plotted.

This chapter investigates detailed design of innovative PV cladding for offices. The design considers all the components so that comfort condition is provided with minimum energy consumption and associated CO_2 emission. Next chapter illustrates cost and environmental analysis of this design.

6. Cost and environmental analysis

This chapter discusses cost and environmental analysis of two refurbishment options for the assumed office module which is 79.59 m^2. The first option is the designed PV cladding system, while the second one is a new conventional cladding with HVAC system. Carbon payback time of PV panel is calculated. The embodied energy and carbon of PV system is estimated using data from the literature. Cost analysis considers undiscounted and discounted savings of implementing the PV cladding refurbishment option over a conventional one. Currently grants to encourage BIPV range from 40% to 65% (DTI[1] 2005), so PV capital costs are calculated with and without grants. Before doing the analysis, it is proposed to find out how much of required energy is provided by PV.

6.1. Office energy demand

Office is occupied during the day, when electricity is being generated by PV. Energy requirements of fan with heat recovery and part of lighting are assumed to be provided by PV. Table 6.1 presents daily ventilation and lighting energy consumption as well as average daily electricity generated by PV. For more detail see table V.1 in appendix V.

Table 6.1: Average daily PV energy output, ventilation and lighting consumption

Month	Average PV electricity output over a day (kWh/day)	Average ventilation consumption (kWh/day)	Average lighting consumption (kWh/day)
January	1.12	0.49	4.43
February	2.03	0.49	2.15
March	3.25	0.49	2.21
April	3.77	0.49	0.36
May	3.61	0.24	0.14
June	2.95	0.24	0.15
July	3.75	0.24	0.11
August	4.40	0.24	0.48
September	4.01	0.24	1.55
October	2.73	0.24	2.56
November	1.79	0.24	4.16
December	1.09	0.24	4.51

Table 6.1 shows that on average PV system is able to provide electricity required by fan, but it cannot provide 100% of office lighting electricity from October-February (based on average daily PV output and daily lighting requirements it is calculated that PV can provide 53% of lighting requirements, for more detail see table V.2 in appendix V). So PV system is an auxiliary system, which requires a conventional system as back up. In order to minimize capital and running costs, it is proposed that PV cladding is not connected to the grid and there is no inverter, but there is some battery back up to be charged in days of high sun and discharged in days of lower sun. Additionally, PVs directly power the fan using DC; also lighting connected to PV will use DC. When there is low PV power generated, auxiliary lighting system is needed; the detailed design of the electrical system is not considered in this study. Since detailed design of electrical system of lighting is not considered and probable shading of cladding structure on PV is assumed as negligible, therefore, in order to estimate the actual savings, any saving regarding lighting system are not considered in the cost and environmental analysis.

6.2. Carbon payback time

Due to lack of data, carbon payback time is only calculated for PV itself. This is total embodied energy of PV system divided by carbon saving per year. The energy in the PV material is assumed to be from electricity. The full embodied energy of the PV system, including the module and the balance of system (BOS) components, is found to be 1262.60 MJ/m^2 (350.72 kWh/m^2) (Croxford and Scott 2006).

Table 6.2: Carbon payback time of PV panel (9.60 m^2)

PV embodied energy (kWh)	PV embodied carbon (kg CO_2)	Energy saving by PV (kWh/yr)	Carbon saving by PV (kgCO_2/yr)*	Carbon payback (yrs)
3366.93	1750.80	1050.59	546.31	**3.20**

* Electricity CO_2 emission factors: 0.52 kgCO_2/kWh (Anon, 2003a)

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6.3. Economic analysis

Undiscounted and discounted savings of implementing the designed refurbishment option instead of a conventional one are calculated for an assumed office module with total floor area of 79.59 m^2. In order to calculate the savings first capital and running costs of each component integrated into the PV cladding and the conventional option are calculated. Following sub-sections describe their capital cost and running costs.

6.3.1. Capital and running cost of new PV cladding system

In order to calculate capital and running costs of the PV cladding system, costs of its facade, PV, fan with heat recovery and electrical heater are calculated.

Facade capital and running cost

As openings are manually controlled and there is not any motorized part, it is supposed that façade cost is the same as that of a typical one. According to Zammett, D (Personal communication, August 21, 2006) a typical office facade is approximately 350 £/m^2. The only maintenance is cleaning which is not taken into account. Table 6.3 presents capital cost of south façade of the assumed office space.

Table 6.3: Capital and running costs of south façade of the office module

	South facade area (m^2)	Capital cost (£)	Annual running cost (£)
Facade	21 (6.00*3.50)	7350	-

PV capital and running cost

According to Lashford, S (Personal communication, Jul 19, 2006) total cost of 1000 £/m^2 is considered for PV integrated into façade, including its installation costs. However, as mentioned above a 60% grant can be obtained, so capital costs with and without grant are calculated.

Since there is no inverter, maintenance for photovoltaic system is assumed to include only an electrical inspection of the system every 5 years. At today's prices, an electrical inspection is about £ 200 (Croxford and Scott 2006). Basically, electrical inspection is for the whole PV system integrated into facade, and it is assumed that above mentioned electrical inspection is for every 20 modules. It is supposed that there is an electrical inspection in the last year. Maintenance cost of battery is assumed to be included in electrical inspection cost. Table 6.4 presents PV capital cost (with and without grant) as well as its running cost.

Table 6.4: Photovoltaic capital and running costs (PV area: 9.60 m^2)

	Capital cost (excl grant) (£)	Capital cost (incl grant) (£)	Cost of electrical inspection (every 5 years) (£)	Maintenance cost during lifetime (£)	Annual running cost (£)
Photovoltaic	9600	3840	10	60	2

Fan and heat recovery capital and running cost

According to Jones, T, (Personal communication, Aug 21, 2006) the trade price of selected fan (LoWatt TX9WL) is approximately £ 360 each and its motor is designed for a 70,000 hours life under normal circumstances, so fan lifetime is around 30 years. Since heat recovery is considered, it is proposed to design a heat recovery ventilation system which uses two fans. Heat recovery device capital cost is assumed as £ 200.

The only maintenance for fan itself is cleaning; however the quality of supplied air is affected by filter and it should be changed every 3 months. Due to lack of data, it assumed that filter replacement and other maintenance during the whole life of system cost 0.2% of capital cost. Since fans and heat recovery runs by PV power, their annual energy consumption is not taken into account. Table 6.5 presents fan and heat recovery capital and running cost for the assumed office space.

Table 6.5: Fan and heat recovery capital and running costs for the assumed office module

	Capital cost (£)	Maintenance cost during lifetime (£)	Annual maintenance cost (£)
Fan	720	1.44	0.05
Heat recovery	200	0.40	0.01
Total system	920	1.84	0.06

Electrical heater capital and running cost
The trade price of a 3 kW electrical heater is approximately £ 26 (Anon 2006c). No maintenance cost is assumed for heater; however it is proposed to change the heater every 10 years. It is assumed that the heater is used for a maximum of 50 hours/yr (i.e. when internal temperature is lower than 21°C). The calculations assume that during this time it is operated at full power, in reality it is likely to be much lower energy consumption that that shown here. Table 6.6 shows electrical heater capital and running costs.

Table 6.6: Electric heater capital and running costs for the assumed office module

	Capital cost(£)	Annual maintenance cost (£)	Energy consumption (kWh/yr)	Annual energy consumption cost (£)*	Annual running cost (£)
Electric heater	78	0.00	150	11.25	11.25

* Electricity cost: 0.0.75 £/kWh (Croxford and Scott 2006)

Table 6.7 presents a summary of total capital and running costs of PV cladding system.

Table 6.7: Total capital and running costs of the PV cladding design for the assumed office module (79.59 m^2)

	Capital Cost (excl grant) (£)	Capital Cost (incl grant) (£)	Annual running cost (£)
PV cladding system	17948	12188	13.31

6.3.2. Capital and running cost of a conventional new facade with HVAC system
In order to calculate capital and running costs of a typical cladding with HVAC, costs of its new facade and HVAC are calculated.

Facade capital and running cost
Capital cost of new facade of the south façade is assumed the same as calculated in table 6.3 (i.e. 7350 £).

HVAC capital and running cost
According to capital and maintenance costs given by Pennycook et al (2003), it is found that capital cost of HVAC system is around 103-227 £/m^2 (assumed to be 165 £/m^2) and its maintenance cost is 750 £/100m^2. Moreover, based on annual delivered energy consumption of an air-conditioned office space (Good practice) presented in ECON19 (Anon 2003a), it is calculated that heating, cooling and ventilation energy consumption in an air-conditioned office space (standard type) are 77.60, 14 and 28.50 kWh//(m^2.yr) respectively, for more detail on energy consumption estimation see appendix W. Table 6.8 presents HVAC capital and running cost of a HVAC system for assumed office module.

Table 6.8: HVAC capital and running costs of a typical air-conditioned office module (79.59 m^2)

	Capital cost (£)	Annual maintenance cost (£)	Electricity energy consumption (kWh/yr)	Gas energy consumption (kWh/yr)	Annual energy consumption cost (£)*	Annual running cost (£)
HVAC	13132.35	596.92	3382.58	6176.18	333.98	930.90

* Gas cost is assumed 0.013 £/kWh (Anon 2003a), Electricity cost is assumed 0.075 £/kWh (Croxford and Scott 2006)

Table 6.9 presents summary of total capital and running costs of a refurbishment option considering new facade with HVAC system for assumed office module.

Table 6.9: Total capital and running costs of a new conventional facade with HVAC system of a similar air-conditioned office module (79.59 m^2)

	Capital Cost (£)	Annual running cost (£)
New facade and HVAC system	20482.35	930.90

6.3.3. Undiscounted saving
Since both the capital and running costs of the PV cladding system are less than that of a conventional one, it is proposed to calculate undiscounted and discounted savings over the life time of the PV cladding system (i.e. 30 years). Table 6.10 presents savings in capital and running costs when implementing the PV cladding system instead of a new cladding with HVAC system.

Table 6.10: Saving in capital and running costs by implementing PV cladding for the assumed office module (79.59 m^2)

Saving in capital cost (excl grant) (£)	Saving in capital cost (incl grant) (£)	Saving in annual running cost (£)
2534.35	8294.35	917.59

Undiscounted saving is the saving in initial capital cost added by saving in running cost during 30 years. Table 6.11 presents undiscounted saving of implementing the PV cladding design instead of a typical air-conditioned one for the assumed office module during 30 years.

Table 6.11: Undiscounted saving for the assumed office module (i.e. 79.59 m^2) during 30 years

	Undiscounted saving (£)
Excluding grant	30062.05
Including grant	35822.05

Table 6.12 presents undiscounted saving per square meter of office module during 30 years.

Table 6.12: Undiscounted saving per square meter during 30 years

	Undiscounted saving (£/m^2)
Excluding grant	377.71
Including grant	450.08

Undiscounted saving does not consider fuel price rise and value for the money, so it is proposed to calculate discounted saving as well.

6.3.4. Discounted saving

Discounted saving presents the saving in the financial investment, including future maintenance costs and a social discount rate. A social discount rate of 3.5% is assumed as this is the current rate used by the UK treasury (Croxford and Scott 2006). Future fossil fuel price rise is currently uncertain. Therefore, two different price rise scenarios are considered, the first one considers fossil fuel prices rise at the same rate as the social discount rate (i.e. 3.5%), while the second one considers the current rise (i.e. 10%) (Croxford and Scott 2006). Using following formula, discounted saving of implementing PV cladding system instead of a conventional one during 30 years is calculated.

$$\text{Discounted saving} = C + R\sum_{t=1}^{t=n} \frac{(1+f)^t}{(1+i)^t}$$

C is the saving in initial cost of measure
R is the saving in annual running cost of measure
f is the average rate of increase of fuel prices
i is the discount rate
n is the lifetime of the measure (years)

Table 6.13 presents discounted saving of implementing the PV cladding design instead of a conventional one for the assumed office module during 30 years.

Table 6.13: Discounted saving for the assumed office module (i.e. 79.59 m^2) during 30 years

	Discounted saving, fuel rise 3.5% (£)	Discounted saving, fuel rise 10% (£)
Excluding grant	30062.05	83548.37
Including grant	35822.05	89308.37

Considering fuel price rise at the same rate as the social discount rate results in a discounted saving the same as undiscounted one. However, assuming 10% increase in fuel price, brings the discounted savings during 30 years to 1049.73 and 1122.11 £/m^2 excluding and including grant respectively. Table 6.14 presents discounted saving per square meter of office module during 30 years.

Table 6.14: Discounted saving per square meter during 30 years

	Discounted saving, fuel rise 3.5% (£/m^2)	Discounted saving, fuel rise 10% (£/m^2)
Excluding grant	377.71	1049.73
Including grant	450.08	1122.11

As table 6.15 shows implementing this PV cladding system instead of a conventional one results in almost 97% decrease in annual CO_2 emission related to heating, cooling and ventilation.

Table 6.15: Impacts of refurbishment options on annual CO_2 emission of assumed office module (79.59 m^2)

	Total gas (kWh/yr)	Total electricity (kWh/yr)	Total CO_2 emission ($kgCO_2$/yr)*
PV cladding system	-	150	78
Air-conditioned standard (Good practice)	6176.18	3382.58	2932.42

* Gas CO_2 emission factors: 0.19 $kgCO_2$/kWh, Electricity CO_2 emission factors: 0.52 $kgCO_2$/kWh (Anon, 2003a)

Table 6.16 illustrates impacts of both refurbishment options on annual CO_2 emission per square meter of assumed office module.

Table 6.16: Impacts of refurbishment options on annual CO_2 emission per square meter of assumed office module

	Total CO_2 emission ($kgCO_2/(m^2.yr)$)
PV cladding system	0.98
Air-conditioned standard (Good practice)	36.84

As it is mentioned previously, heating consumption and its associated CO_2 emission are expected to be less in use phase than that calculated here, so it is expected that this PV cladding can result even in more saving and less CO_2 emission in reality than that shown here.

This chapter considers cost and environmental analysis of innovative cladding design and presents advantages of implementing the PV cladding design as a refurbishment option over a conventional one. Next chapter presents findings of this study as well as the ways it can be continued in future.

7. Conclusion

This part reviews the results and interpretations presented previously. It also briefly summarizes the main findings, indicates limitations of the study and suggests future directions for further research.

7.1. Design process and findings

Interest in building integrated photovoltaics (known as BIPV), where the PV elements are integral to the building is growing worldwide. So this study proposes a PV cladding design for office buildings refurbishment which not only incorporates photovoltaic power, but also controls solar radiation, provides daylight, natural and mechanical ventilation (powered by PVs). The integration of this PV cladding design into office façade refurbishments offers substantial opportunities for reducing building energy consumption both through direct electricity generation, and reduction of energy consumption and need for an HVAC system.

The PV cladding is designed for an assumed office module (6.30 m by 13.50 m by 3.50 m). It is found that office buildings with this innovative cladding design have the potential to contribute significantly to energy supply and consequently to reduce CO_2 emissions, while at the same time providing recommended comfortable conditions. This innovative PV cladding is designed by adopting conventional components as required. The PV cladding design incorporates several components including PV panels, fan with heat recovery, and window with openings at different levels.

Cladding components and materials are not only selected based on their efficiencies, cost, mechanical resistance and stability, but also based on their impacts on the environment and health. For glazing surfaces, based on transmittances and U-Values of different glazing types, low-e double glazing (U-Value: 1.8 W/(m^2.K), 0.65 visible transmittance and 0.40 solar transmittance) is proposed. The window frame and non glazed portion of façade approximately constitutes 35% of the façade. For non-glazed portions, material proposed is recycled aluminium with thermal break which is light, maintenance free and long life material. Considering its environmental impact, it is found that over 60% of the energy required to extract aluminium worldwide is generated from renewable sources, also after recycling, used aluminium still retains its quality characteristics.

To select other components, (i.e. PV, fan and heat recovery), their efficiency and capital cost are taken into account, so PV type of Monocrystalline silicon with total system efficiency of 12% is selected. For ventilation, LoWatt TX9WL fan, a high performance extract/intake ventilating unit is selected, and a heat exchanger plate (70% efficiency) is proposed for heat recovery device.

The main intention in cladding design is to find an optimum design solution for each element. The angle of the PV cell is planned to be flexible changing according to the maximum energy output. Investigations show that in order to get the maximum possible energy output, the optimum PV tilts should differ seasonally, in such a way that during winter time it is 67.5°, in mid-season 45° and in summer 22.5°. Also, banks of PV arranged on the cladding might produce a degree of self-shading which lower the annual output. Considering the maximum energy output of different PV lengths, the optimum suggested length is a PV panel 1.60 m long.

PV panels are applied not just to generate electricity, but also to improve general aspects including the use of diffuse daylight, shade provision and aesthetical contribution to the interior view and exterior of the office. Some PV positions are simulated (in TAS and AGI32) to find out the impacts of various PV positions on internal lighting, cooling and heating consumption, and two optimum positions (for heating and cooling period) which helps to cut annual energy consumption are selected. In the mean time, adequate glazed areas (approximately 65% of surface area) for daylight, while controlling excessive solar gain are proposed. Considering transparency of 50% for PV cells and based on analysis, it is proposed to install 3 PV panels 0.53 m long instead of a 1.60 m one.

In order to assess ventilation strategy, using simulations in TAS, mechanical ventilation strategies with and without heat recovery are considered, it is found that with heat recovery, the building is colder than 21°C for only 50 hours during the heating period. In order to omit entirely the need for central heating, it is proposed to consider a 3 kW electric heater to provide comfort conditions when the internal condition is cold. It is calculated that considering a 3 kW heater, if the building is heated during all the 50 hours heating consumption will only be 1.88 kWh/(m^2.yr) and importantly the increased capital cost will be tiny. However, if occupants are prepared to accept just 50 hours in a year with temperature below 21°C (e.g. by wearing more clothes), then no heating is required.

During the cooling period secure night ventilation is provided via separate openings, and appropriate control is suggested to avoid overcooling the space. Thermal contact between the ventilation air and thermally massive concrete structure and ceiling slabs is ensured. Considering night ventilation and supplying pre-cooled fresh air by fan, it is found that internal condition is only hotter than 25°C (when

the external is also hot) for 193 hours a year. So depending on the acceptance of the occupants, it is proposed to provide higher fan speeds on hot days so that this extra air movement helps to provide comfort conditions during summer time. Providing higher fan speeds on hot days does not cause any increase in energy consumption, because the selected fan consumes 27 W when running at its high speed, but ventilation consumption is calculated as if the fan consumes 27 W all the time. It is calculated that ventilation consumption considering heat recovery is 0.88 kWh/(m^2.yr).
Due to a design process which considers daylight, good lighting design is able to save 70% energy. However, this can only be achieved by good lighting controls as well as educating occupants. The lighting consumption is calculated to be 6.27 kWh/(m^2.yr).
Assuming that the building is not shaded either by landforms or surrounding buildings, on average PV panels (9.60m^2) are able to provide the energy required by fan and heat recovery all the time, also considering available daylight, PV panels are able to generate 100% energy required for lighting during March-September.
Possible negative environmental impacts of PV systems, including impacts from production of the components of PV and from daily operation of the PV system, are considered. Based on investigations, it is found that all PV system life cycle CO_2 emissions are indirect ones which results from the manufacturing process. Analysis shows that PV panel integrated into the façade module has a carbon payback time of 3.20 years which is about 10% of its life time.
Implementing this innovative PV cladding design as the refurbishment option instead of a conventional system (i.e. new cladding with HVAC) results in undiscounted saving of 377.71 and 450.08 £/m^2 without and with grant respectively during 30 years (i.e. system life time). Assuming fuel price increases at the same rate of social discount rate (i.e. 3.5%) results in a discounted saving equals to that of an undiscounted one. But considering the energy price increase at its current rate (i.e. 10%), discounted saving of 377.71 and 450.08 £/m^2 (excluding and including grant respectively) can be achieved during 30 years. Although PV is very expensive, due to the reduction in need for HVAC system, this cladding system is much cheaper when compared to a conventional one. Moreover, this innovative cladding results in 97% decrease in annual CO_2 emission associated to heating, cooling and ventilation compared to that of a conventional one.
Considering costs and CO_2 saving which can be achieved by implementing this innovative cladding design instead of a conventional one, it can be stated that this PV cladding design is an excellent investment for office buildings refurbishment.

7.2. Future of the study

Since simulation software such as TAS and AGI32 are not sufficient to analyze the performance of this PV cladding design, it is proposed to test this innovative cladding design at least in a laboratory or even in outdoor under natural conditions in different seasons to find out its performance, and verify if it causes any overheating, light-glare or even high electricity consumption.
Moreover, this study assumes that the office site is not shaded, but there are not many unshaded sites in London. If photovoltaics are obstructed, either by landforms or surrounding buildings, output will obviously fall and an assessment will need to be made of the probable energy loss. Based on calculations PV is all the time able to provide electricity required by fan and heat recovery in this site, so considering a site which is 50% of the time shaded, it is estimated that the PV is still able to provide a large proportion of the energy required by fan and heat recovery. But it is suggested to consider any shading in detail in future research studies.
Moreover, cost and environmental analysis can be reviewed in more detail to analyze a wider range of social and economic effects of the design, considering the whole system design compared to a conventional one. Since the detailed design of electrical lighting system is not considered in this study, this can be a suitable field for further research which can also include its impacts on cost and environmental analysis.
It is also important to investigate ways by which this cladding system could be applied on east and west facing facades.
Finally, it is proposed to present flexible standards for this cladding system to be able to be implemented in a wider range of offices in UK or even around the world.

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9. Appendices

Appendix A

Window frame material

Windows should be durable and economical with the least possible cost. Selection of window frame material in this study is not only based on their cost, mechanical resistance and stability, but also on their impact on the environment and health. The environmental impacts include ecological degradation due to extraction of raw materials and pollution from manufacturing product process. As Baitz et al (2004) mentions, the principal competing window frame materials are PVC, wood and aluminium. Steel, stainless steel, wood/aluminium, ferrous metals and other polymers play a minor role. Most of the studies by Baitz et al (2004) show that above mentioned frame materials (PVC, aluminium and wood) have their own strengths and weaknesses, and none of the studies proposes a winner in terms of a preferable material.

The same study shows that reducing environmental impacts of windows is expected to be through the optimization of the design and specific construction processes, which means increasing the quality of the windows with respect to their main function of saving heating energy in the use phase. Therefore the choice of material is of rather minor importance, as long as the material can provide the required system quality of a window. According to a study by Baitz et al (2004), the use phase (i.e. function, maintenance demands and durability) is the most important part of the life cycle of windows, so in this study the window frame material is selected, considering its use phase, but its environmental impacts during manufacturing process are also considered.

Baitz et al (2004) mention that aluminium frame (if not recycled) causes high burden to the environment because of the dangerous pollutants released. However, according to technical information (Schueco 2006), it is found that over 60% of the energy required to extract aluminium worldwide is generated from environmentally friendly, renewable sources, namely water power. As Baitz et al (2004) mentions PVC contributes large amounts of poisonous pollutants throughout its life cycle, while timber window frames have the least environmental burdens. But the timber window frame requires frequent surface treatment during the use phase to maintain its technical and thermal properties. The coating of the wood surface causes significant emissions in the category of eco-toxicity. Even water based paint systems do not manage to substitute solvents entirely, and not all possible paint systems give enough protection for window applications. Moreover, the natural production of wood and its harvesting causes environmental consequences (e.g. cultivating, harvesting, drying, transport).

Additionally, embodied energy analysis of a 1.2 m × 1.2 m window done by Asif et al (no date) shows that aluminium (not recycled), PVC and timber windows have embodied energy of 6 GJ, 3GJ and 1GJ respectively, recycled aluminium has an embodied energy close to that of PVC. The same study shows that all frame materials deteriorate to various degrees by environmental impacts. PVC is sensitive towards heat and UV radiation. Timber if not frequently treated, can easily be affected by environment. Aluminium, if not protected well by coatings, gets damaged under corrosive conditions especially in coastal and industrial areas. The survey analysis (Asif et al, no date) shows that aluminium and timber windows can easily last more than 40 years. PVC windows, in most cases, are reported to have an optimum service life of 25 years.

From economic point of view, there is no standard procedure to compare the capital cost of frames of different materials. In terms of maintenance cost a study by Asif et al (no date) shows that timber windows are the most expensive as they require regular maintenance of the frame i.e. painting or staining after every 5 years. Aluminium frames need only to be cleaned to maintain their bright appearance. PVC frames should be cleaned with alkaline detergents after every 6 months to maintain their appearance. Another economic aspect of windows is their running cost (i.e. energy cost in the form of heat loss through them). According to studies (Asif et al, no date) aluminium with thermal breaks, timber and PVC windows have all good thermal resistance.

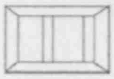
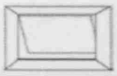
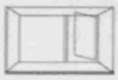
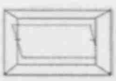
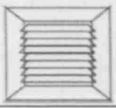
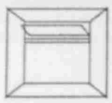
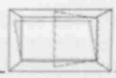
Most of the studies conclude that no material has advantages in all impact categories. Highest potentials for improvement are expected in the optimization of the frame structures. According to disadvantages that timber window frame cause to the environment, in this study it is proposed to use either PVC or recycled aluminium with thermal breaks, which have almost the same embodied energy, running and energy cost. However, recycling PVC face a lot of barriers at the moment and PVC life time is far less than recycled aluminium, so the material selected for window frame is recycled aluminium, considering a window U-Value of 1.80 $W/(m^2.K)$.

Appendix B

Window openings

According to Rennie and Parand (1998) in summary regarding window shapes, tall windows with their heads near the ceiling use the stack effect on still days better than horizontal windows as well as providing better view and daylight. Gold and Martin (1999) believe that the choice of window is important for a number of reasons including ventilation capacity, ease of opening, security, seal effectiveness and interference with blinds. Table B.1 compares advantages and disadvantages of different window openings. As the table B.1 presents, each of opening types has its own advantages and disadvantages, so this study proposes to consider the window with separate opening elements at different levels to provide the requirements.

Table B.1: Advantages and disadvantages of different window types (Kendrick et al 1998, p.35)

Window type		Advantages	Disadvantages
	Sliding window / horizontally sliding sash	Relatively low cost Tall opening for localized stack ventilation Safe in high winds Unobstructed large open area for air flow Large panes (weight easily supported) Good noise attenuation (as double window) No external projections for bird fouling, etc. No internal projections to interfere with blinds BMS controllable	Not secure for night ventilation Rain penetration possible Desk-level draughts
	Top hung, outward opening casement vent	Good weather protection Scoops upward air flow (solar plume) into building Secure night ventilation (if small) BMS controllable	Could reflect noise into room Fine (manual) control difficult Subject to bird fouling
	Side hung casement window	Tall opening for localized stack ventilation BMS controllable Simple intuitive control Good outside awareness	May lack fine ventilation control for winter Unsuitable for high wind speeds Size limited by weight concern Lack of security when open Rain penetration possible Desk-level draughts
	Horizontal pivot window	Upper and lower vent for stack flow Easy access for cleaning BMS controllable High air flow rates when used for single sided vent	May lack fine ventilation control for winter Angle of opening limited for safety Could reflect noise into the room Desk-level draughts possible Opening restricted by internal blinds Top seal difficult if control at bottom
	Louvre window	BMS controllable Secure night ventilation	Difficult to seal effectively Relatively expensive and complex Could reflect noise into the room
	Window with bottom hung inward opening hopper or top vent	Directs air at ceiling for night cooling No projections for bird fouling, etc. Secure night ventilation BMS controllable Direct sound to ceiling (absorbent) No projections for bird droppings etc.	Rain penetration possible May lack fine control for winter Could interfere with internal blinds
	Tilt and turn window	Easy access for cleaning	Relatively expensive and complex BMS control in one orientation only Fine (manual) control difficult
	Vertical double sash	Good single-sided ventilation (upper/lower) No external projections for bird fouling, etc. No internal projection to interfere with blinds Unobstructed large open area for air flow BMS controllable	Difficult to seal effectively Rain penetration possible

Appendix C

Selected fan, LoWatt TX9WL

Figure C.1: Fan performance (Vent-axia 2006)

Performance

Unit Size		LoWatt TX9WL Wireless	LoWatt TX9WL
Stock Ref. No.		45 61 70	45 61 66
Amps @ 240V		0.31	0.31
Extract Performance m³/h	Low	326	326
	Med	562	562
	High	732	732
Watts (high)		27	27
dB(A) (med) @ 3m		39	39

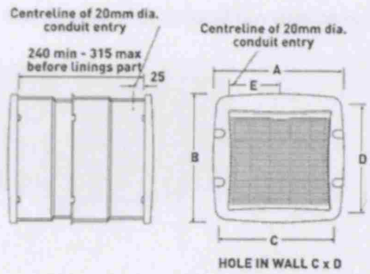
Unit Size		LoWatt TX12WL Wireless	LoWatt TX12WL
Stock Ref. No.		45 61 78	45 61 74
Amps @ 240V		0.70	0.70
Extract Performance m³/h	Low	660	660
	Med	1355	1355
	High	1650	1650
Watts (high)		68	68
dB(A) (med) @ 3m		48	48

Recommended Controller:
Wire-less Controller **Stock Ref. No. 45 58 74**
Wired Controller **Stock Ref. No. 45 58 73**

Figure C.2: Fan dimensions (Vent-axia 2006)

Dimensions (mm)

Size	A	B	C	D	E	F	Weight kg
230mm	391	388	365	375	143	54	7.77
300mm	470	467	442	450	182	54	10.864



Appendix D

Heat recovery

According to Barnard et al (2001) there are technical considerations to take into account when selecting heat recovery devices which include:

- Heat recovery efficiency (sensible and total)
- Airflow arrangement
- Fouling (filters should be placed in both supply and exhaust air streams)
- Corrosion (particularly in process applications)
- Cross-contamination
- Condensation and freeze-up
- Pressure drop
- Face velocity
- Construction materials (suitability for temperatures, pressures, contaminants)
- Maintenance (in particular cleaning of surfaces)
- Controls

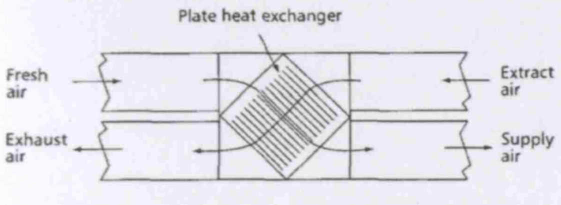
But the only appropriate heat recovery device for this study is plate heat exchangers and it is described below.

Cross-flow plate heat exchangers are inexpensive, have low hydraulic resistance and require no motive power. Jones et al (2004) describes that effectiveness can be in the range 30-70%, depending on the spacing of the plates. The advantages and disadvantages are summarized in Table D.1. Placing the fan on the downstream side of the device on the supply side and the upstream side on the exhaust side maximizes the ability to pick up the fan energy.

Table D.1: Advantages and disadvantages of heat exchangers (Jones et al 2004, p.4-13)

Advantages	Disadvantages
Simple static devices; easy to commission and maintain	No modulation, so rate of heat recovery cannot be controlled unless a by-pass duct is provided (i.e. overheating could occur when heating requirements are small); over-recovery of heat also possible if there is a building cooling requirement (i.e. could result in heat being dumped into a cooled space, thereby increasing the cooling load)
Minimal risk of cross contamination unless mechanical damage occurs	Supply and exhaust ducts must be adjacent, and ductwork needs to be arranged to allow heat transfer through the plates
May be constructed so as to be easily removed for cleaning	

Figure D.1: Plate heat exchanger (Henderson et al 2005, p.2-117)



If heat recovery is needed, it is proposed to design fan with heat recovery system, using two LoWatt TX9WL fans combined with a plate heat exchanger. The following figures illustrate its approximate size and images.

Figure D.2: Image of proposed fan with heat recovery (Vent-axia 2006)

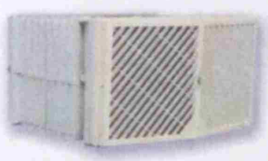


Figure D.3: Fan with heat recovery operation (Vent-axia 2006)

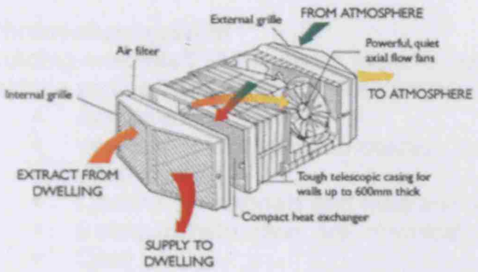
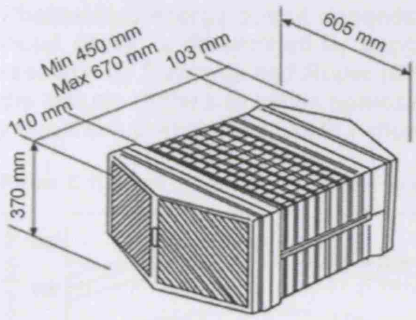


Figure D.4: Fan with heat recovery dimensions (Vent-axia 2006)



Appendix E

Photovoltaic system

Building-integrated PV systems need to play the same role as the traditional cladding elements they replace and as Thomas et al (1999) propose, PV systems must address all the normal issues, like:

- Appearance
- Weather tightness and protection from the elements
- Wind loading
- Lifetime of materials and risks and consequences of failure
- Safety (construction, fire, electrical, etc)
- Cost

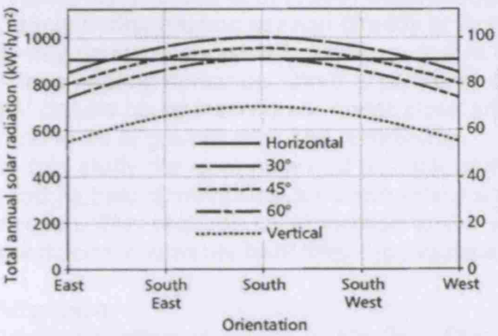
In this part factors affecting energy output of PV array are considered in detail.

Factors affecting energy output of PV array

Solar radiation

Photovoltaic energy output depends on solar energy. The amount of solar radiation, varying due to cloud cover, is determined by geographical location, tilt and orientation of the modules. Based on research by Rawlings and Roper (2000) orientation due to south and a tilt from the horizontal equal to the latitude of the site minus approximately 20˚ has the maximum total annual solar radiation, e.g. 30˚ in southern England. Figure E.1 shows the effect of tilt and orientation on energy output.

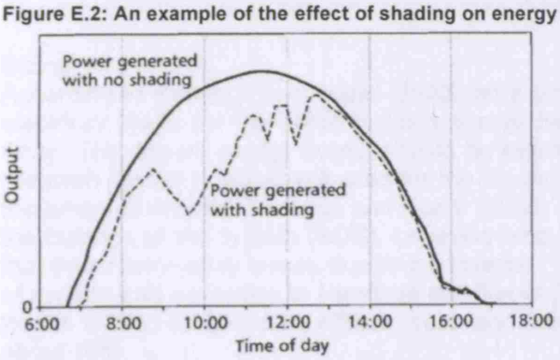
Figure E.1: Effect of tilt and orientation on energy output (Rawlings and Roper 2000, p.4)



Shading

According to Rawlings and Roper (2000), since the cell with the lowest illumination determines the operating current of the series string in which it is connected, minor shading can result in a significant loss of energy. So in order to use electricity produced as much as possible, self-shading should be avoided. Figure E.2 shows an example of the shading effect.

Figure E.2: An example of the effect of shading on energy output of a PV array (Rawlings and Roper 2000, p.4)

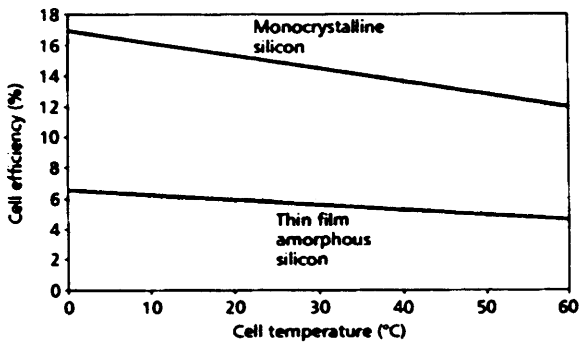


Temperature

Rawlings and Roper (2000) mention that PV cells available in market convert under 20% of the incident solar energy into electricity and much of the rest of the energy is converted to heat. Modules can reach temperatures of 40°C or more above ambient, if this heat is not removed. According to

Rawlings and Roper (2000) for every degree rise in temperature, efficiency of monocrystalline silicon cells and amorphous silicon cells decrease by 0.45% and 0.25% respectively. Figure E.3 shows how efficiency of PV cells falls as their temperature rises.

Figure E.3: Impacts of temperature on cell efficiency (Rawlings and Roper, 2000, p.4)



Obviously, adequate ventilation is necessary in order to keep the temperature as low as possible to improve module performance. There are many ways of doing this, varying from ventilation gaps in cladding to combining the module ventilation with the building ventilation. According to Thomas et al (1999) a rule of thumb is to provide an air gap of 100 mm, and the same study indicates that performance is improved with gaps up to 200 mm or more.

A study by Thomas et al (1999) explains that it is possible to use heat given off at the back of the PV panels during heating season directly or to recover it by a system of ducting. But the study shows that it may not be economically viable to do it in highly energy-efficient buildings which often have very low space heating demands. Other possibilities of using the waste heat explained in the same study is that PV panels could incorporate water pipes linked to space or hot water systems but these possibilities tend to be of greater cost and complexity.

In this study the heat given off at back of the panels is not used. But it is important to consider that module heat does not cause overheating and contribute to the building's cooling load outside heating season. This requires consideration of the ventilation patterns in building and to ensure that in windy conditions in summer heat from the modules does not lead to discomfort.

Mismatch

Mismatch effect is similar to shading. Study by Rawlings and Roper (2000) shows that if cells with different performance characteristics are connected in series the poorest module determines the current so the modules in a string need to be closely matched.

Soiling

The degree of soiling depends on location but according to Rawlings and Roper (2000) usually if the array tilt is at least 15°, dust accumulation and self-cleaning result in a steady state after a few weeks. The same study shows that in extreme cases dust may cause a power reduction of about 10%.

Sizing

According to Rawlings and Roper (2000), an estimate of energy output from the PV system and typical electricity loads for the office building should be used as the basis for approximately sizing of PV array. The annual energy output should be estimated using figures for the total annual incident solar radiation for the location, adjusted for the tilt and orientation of the array, and the actual efficiency of the array. Moreover, Rawlings and Roper (2000) describe that allowance has to be made for losses in the balance of the system (BOS), i.e. everything in the system apart from the PV array. They explain that these are mainly losses due to the inverter (10 -15%) and wiring losses (1-3%). The total balance of system loss according to Rawlings and Roper (2000) is typically about 15%. In addition there will be losses due to temperature effects, dust, and mismatch which together reduce the energy output by about 10%.

Additionally, based on study by Thomas et al (1999), there are other particular aspects often associated with being able to use the electricity produced, namely provision of accessible routes for connectors and cables and maintenance.

BIPV systems

Table E.1 lists some of the advantages and disadvantages of photovoltaics in general. It includes both technical and non-technical issues, advantages of BIPV systems are described afterwards.

Table E.1: Advantages and disadvantages of photovoltaics (Luque and Hegedus 2004, p. 3)

Advantages of photovoltaic	Disadvantages of photovoltaic
Fuel source is vast and essentially infinite	Fuel source is diffuse (sunlight is a relatively low-density energy)
No emissions, no combustion or radioactive fuel for disposal (does not contribute perceptibly to global climate change or pollution)	
Low operation costs (no fuel)	High installation costs
No moving parts (no wear)	
Ambient temperature operation (no high temperature corrosion or safety issues)	
High reliability in modules (>20 years)	Poorer reliability of auxiliary (balance of system) elements including storage
Modular (small or large increments)	
Quick installation	
Can be integrated into new or existing building structure	
Can be installed at nearly any point-of-use	Lack of widespread commercially available system integration and installation so far
Daily output peak may match local demand	Lack of economical efficient energy storage
High public acceptance	
Excellent safety record	

Advantages of BIPV systems

With BIPV systems, façade materials and labour to install them are already paid. The land is already paid and the support structure is already in place. As Jones et al (2000) mentions the potential benefits of building integrated photovoltaic (BIPV) include:

- Supply at the point of use
- Silent operation
- Low maintenance
- An inexhaustible supply of clean, free electricity

Also according to Prasad and Snow (2005) BIPV has also more additional benefits like:

- The building itself becomes the PV support structure
- System electrical interface is easy (just connect to a distribution panel)
- BIPV components displace conventional building materials and labour, reducing the net installed cost of the PV system
- On-site generation of electricity offsets imported and often more carbon-intensive energy
- Architecturally elegant (well integrated systems will increase market acceptance)
- BIPV systems provide the building owners with a highly visible public expression of their environmental commitment

Appendix F

Tables F.1 to F.5 show daily incident solar radiation averaged over all weather conditions of south facing facade with five different tilts (90°, 67.5°, 45°, 22.5° and horizontal) on a representative day in each month in London.

Table F.1: Daily incident solar radiation averaged over all weather conditions (kWh/m²), Orientation: South, Tilt: 90° (Page and Lebens1986, p.116)

	January	February	March	April	May	June	July	August	September	October	November	December
Beam	0.56	0.94	1.18	0.98	0.83	0.84	0.76	0.97	1.32	1.24	0.94	0.63
Diffuse	0.33	0.62	1.04	1.38	1.75	1.89	1.81	1.64	1.29	0.81	0.49	0.26
Global	0.89	1.55	2.22	2.36	2.58	2.73	2.57	2.62	2.61	2.05	1.43	0.90

Table F.2: Daily incident solar radiation averaged over all weather conditions (kWh/m²), Orientation: South, Tilt: 67.5° (Page and Lebens1986, p.117)

	January	February	March	April	May	June	July	August	September	October	November	December
Beam	0.58	1.02	1.42	1.39	1.40	1.58	1.39	1.47	1.68	1.40	0.98	0.64
Diffuse	0.39	0.73	1.23	1.67	2.15	2.29	2.23	2.00	1.53	0.94	0.57	0.31
Global	0.97	1.75	2.66	3.06	3.55	3.87	3.59	3.47	3.21	2.34	1.55	0.95

Table F.3: Daily incident solar radiation averaged over all weather conditions (kWh/m²), Orientation: South, Tilt: 45° (Page and Lebens1986, p.118)

	January	February	March	April	May	June	July	August	September	October	November	December
Beam	0.50	0.95	1.45	1.58	1.78	2.12	1.77	1.75	1.78	1.34	0.87	0.55
Diffuse	0.44	0.81	1.37	1.89	2.46	2.63	2.56	2.26	1.69	1.03	0.62	0.35
Global	0.94	1.76	2.82	3.47	4.24	4.74	4.34	4.01	3.48	2.37	1.49	0.90

Table F.4: Daily incident solar radiation averaged over all weather conditions (kWh/m²), Orientation: South, Tilt: 22.5° (Page and Lebens1986, p.119)

	January	February	March	April	May	June	July	August	September	October	November	December
Beam	0.36	0.73	1.25	1.54	1.90	2.37	1.94	1.77	1.62	1.07	0.63	0.38
Diffuse	0.46	0.84	1.42	2.00	2.62	2.81	2.75	2.38	1.75	1.06	0.62	0.37
Global	0.81	1.57	2.67	3.54	4.52	5.18	4.69	4.15	3.37	2.13	1.25	0.75

Table F.5: Daily incident solar radiation averaged over all weather conditions (kWh/m²), Orientation: South, Horizontal (Page and Lebens1986, p.120)

	January	February	March	April	May	June	July	August	September	October	November	December
Beam	0.15	0.40	0.86	1.27	1.74	2.30	1.83	1.53	1.21	0.65	0.29	0.15
Diffuse	0.44	0.80	1.36	1.95	2.59	2.79	2.73	2.31	1.67	1.01	0.58	0.35
Global	0.59	1.20	2.23	3.21	4.33	5.09	4.56	3.84	2.87	1.65	0.87	0.50

Table F.6 presents monthly incident solar radiation averaged over all weather conditions on south facing façade with five different tilts (90°, 67.5°, 45°, 22.5° and horizontal) in London.

TABLE F.6: Monthly incident solar radiation averaged over all weather conditions (kWh/m^2)

Month	South, Tilt: 90°	South, Tilt: 67.5°	South, Tilt: 45°	South, Tilt: 22.5°	South, Tilt: Horizontal
January	27.59 (0.89*31)	30.07 (0.97*31)	29.14 (0.94*31)	25.11 (0.81*31)	18.29 (0.59*31)
February	43.40 (1.55*28)	49.00 (1.75*28)	49.28 (1.76*28)	43.96 (1.57*28)	33.60 (1.20*28)
March	68.82 (2.22*31)	82.46 (2.66*31)	87.42 (2.82*31)	82.77 (2.67*31)	69.13 (2.23*31)
April	70.80 (2.36*30)	91.80 (3.06*30)	104.10 (3.47*30)	106.20 (3.54*30)	96.30 (3.21*30)
May	79.98 (2.58*31)	110.05 (3.55*31)	131.44 (4.24*31)	140.12 (4.52*31)	134.23 (4.33*31)
June	81.90 (2.73*30)	116.10 (3.87*30)	142.20 (4.74*30)	155.40 (5.18*30)	152.70 (5.09*30)
July	79.67 (2.57*31)	111.29 (3.59*31)	134.54 (4.34*31)	145.39 (4.69*31)	141.36 (4.56*31)
August	81.22 (2.62*31)	107.57 (3.47*31)	124.31 (4.01*31)	128.65 (4.15*31)	119.04 (3.84*31)
September	78.30 (2.61*30)	96.30 (3.21*30)	104.40 (3.48*30)	101.10 (3.37*30)	86.10 (2.87*30)
October	63.55 (2.05*31)	72.54 (2.34*31)	73.47 (2.37*31)	66.03 (2.13*31)	51.15 (1.65*31)
November	42.90 (1.43*30)	46.50 (1.55*30)	44.70 (1.49*30)	37.50 (1.25*30)	26.10 (0.87*30)
December	27.90 (0.90*31)	29.45 (0.95*31)	27.90 (0.90*31)	23.25 (0.75*31)	15.50 (0.50*31)

Appendix G

Table G.1: Vertical shadow angle on 21st of March, June, September and December (Suntect, squ1)

Time	VSA	VSA (9:00-15:00)
March-21	21.6 - 38.0	37.7 - 38.0
June-21	61.6 - 79.4	61.6 - 69.8
September-21	39.2 - 60.4	39.2 - 39.8
December-21	6.4 - 14.7	6.4 - 14.7

Appendix H

As following figures show, south facing glazed area (80% or 40%) is not taken into account, because they do not affect the results. Following figures show that when considering no shading, maximum PV lengths on March, June, September and December are 2.77 m, 0.68 m, 1.82 m and 3.40 m respectively.

Figure H.1: Maximum length of PV to provide no self-shading (March-21, tilt: 45)

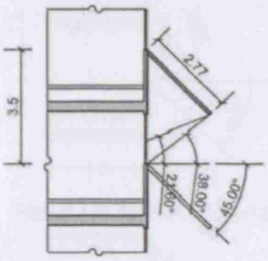


Figure H.2: Maximum length of PV to provide no self-shading (June-21, tilt: 22.5)

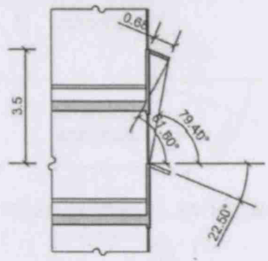


Figure H.3: Maximum length of PV to provide no self-shading (Sep-21, tilt: 45)

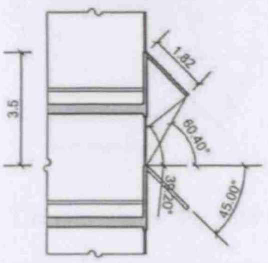
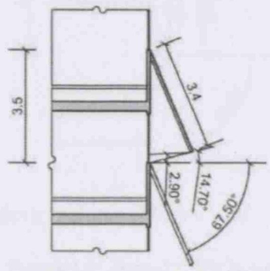


Figure H.4: Maximum length of PV to provide no self-shading (Dec-21, tilt: 67.5)



Where as considering no shading from 9:00 to 15:00, maximum PV lengths on March, June, September and December are 2.77 m, 1.21 m, 2.70 m, and 3.40 m respectively.

Figure H.5: Maximum length of PV to provide no self-shading during 6h/day (March-21, tilt: 45)

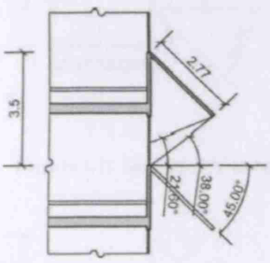


Figure H.6: Maximum length of PV to provide no self-shading during 6h/day (June-21, tilt: 22.5)

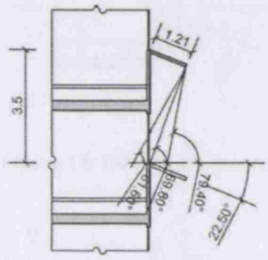


Figure H.7: Maximum length of PV to provide no self-shading during 6h/day (Sept-21, tilt: 45)

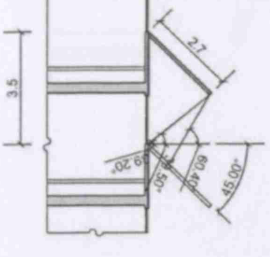
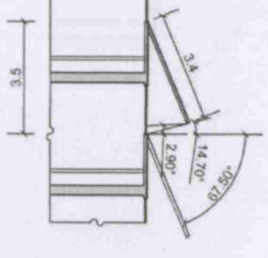


Figure H.8: Maximum length of PV to provide no self-shading during 6h/day (Dec-21, tilt: 67.5)



Appendix I

As following figures show no self-shading occurs during all four representative days, when considering PVs 0.68 m long.

Figure I.1: March-21, PV length: 0.68 m

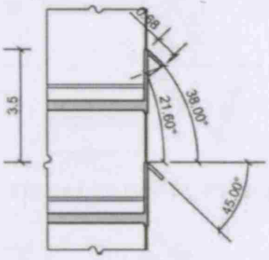


Figure I.2: June-21, PV length: 0.68 m

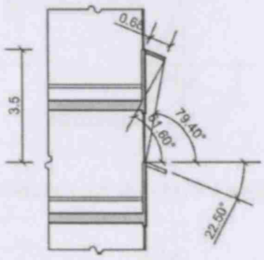


Figure I.3: Sep-21, PV length: 0.68 m

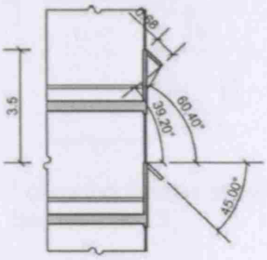
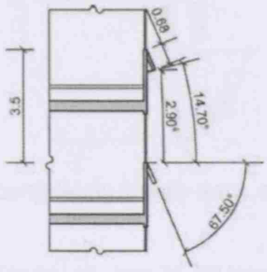


Figure I.4: Dec-21, PV length: 0.68 m



Considering PVs 1.21 m long, some self-shading occurs during June 21.

Figure I.5: March-21, PV length: 1.21 m

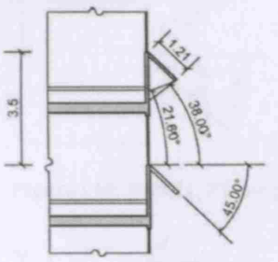


Figure I.6: June-21, PV length: 1.21 m

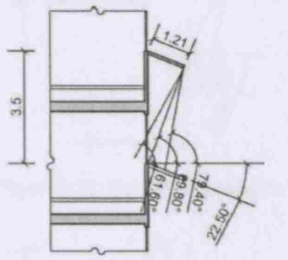


Figure I.7: Sep-21, PV length: 1.21 m

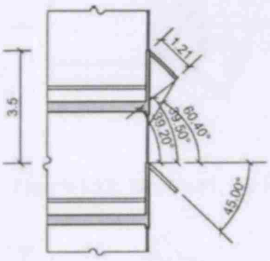
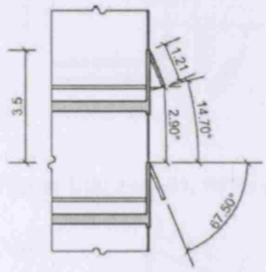


Figure I.8: Dec-21, PV length: 1.21 m



PVs 1.82 m long completely shade each other on June 21.

Figure I.9: March-21, PV length: 1.82 m

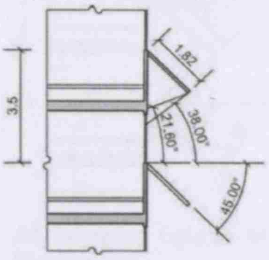


Figure I.10: June-21, PV length: 1.82 m

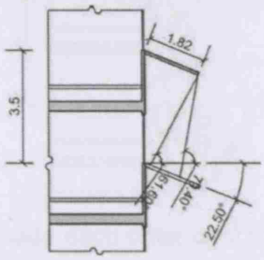


Figure I.11: Sep-21, PV length: 1.82 m

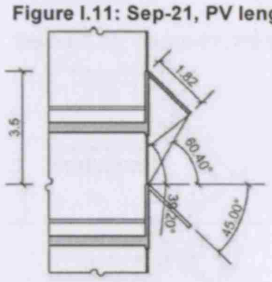
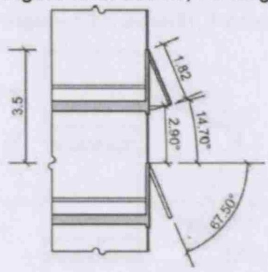


Figure 1.12: Dec-21, PV length: 1.82 m



Following figures show that PVs 2.70 m and 2.77 m long completely shade each other on June 21 and September 21.

Figure I.13: March-21, PV length: 2.70 m

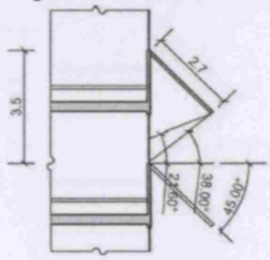


Figure I.14: June-21, PV length: 2.70 m

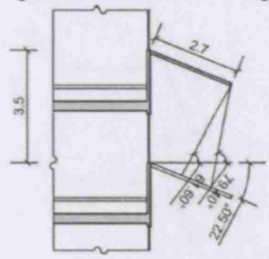


Figure I.15: Sep-21, PV length: 2.70 m

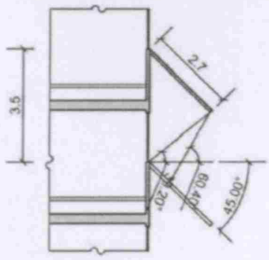


Figure I.16: Dec-21, PV length: 2.70 m

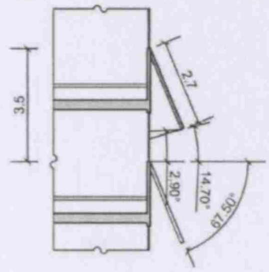


Figure I.17: March-21, PV length: 2.77 m

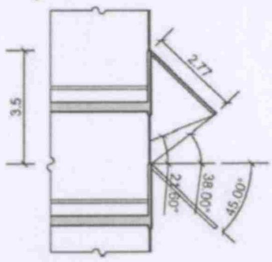


Figure 1.18: June-21, PV length: 2.77 m

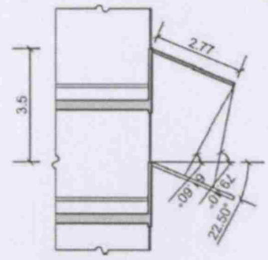


Figure 1.19: Sep-21, PV length: 2.77 m

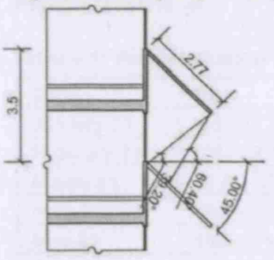
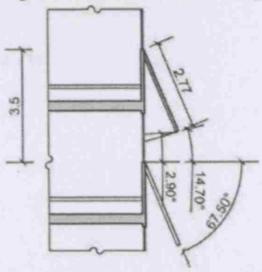


Figure 1.20: Dec-21, PV length: 2.77 m



As following figures show PVs 3.40 m long completely shade each other on 21st of March, June and September.

Figure 1.21: March-21, PV length: 3.40 m

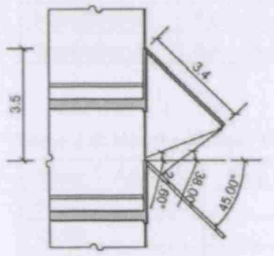


Figure 1.22: June-21, PV length: 3.40 m

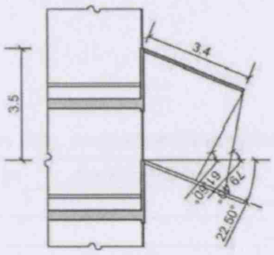


Figure 1.23: Sep-21, PV length: 3.40 m

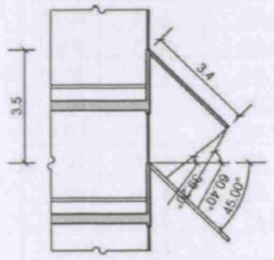
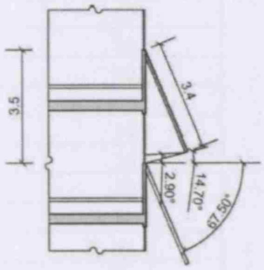


Figure 1.24: Dec-21, PV length: 3.40 m



Appendix J

Table J.1: Vertical shadow angles on 21st of each month (Suntect, squ1)

Time	VSA	VSA (9:00-15:00)
January-21	3.8 - 17.9	9.3 - 17.9
February-21	6.0 - 27.1	21.7 - 27.1
March-21	21.6 - 38.0	37.7 - 38.0
April-21	49.7 - 76.5	49.7 - 54.2
May-21	58.2 - 74.8	58.2 - 65.7
June-21	61.6 - 79.4	61.6 - 69.8
July-21	58.9 - 76.5	58.9 - 66.9
August-21	50.6 - 79.6	50.6 - 55.6
September-21	39.2 - 60.4	39.2 - 39.8
October-21	8.1 - 27.7	22.4 - 24.4
November-21	5.0 - 18.4	9.6 - 18.4
December-21	6.4 - 14.7	6.4 - 14.7

Table J.2: Hourly vertical shadow angles on 21st of April, May, June, July, August and September (Suntect, squ1)

Time	April 21	May 21	June 21	July 21	August 21	September 21
04:00						
05:00						
06:00						60.4
07:00	75.3				79.6	40.9
08:00	59.9	73.3	79.4	76.5	62.2	39.8
09:00	54.0	65.0	69.8	66.9	55.6	39.5
10:00	51.3	60.8	64.9	62.0	52.5	39.3
11:00	50.1	58.7	62.4	59.7	51.1	39.2
12:00	49.7	58.2	61.6	58.9	50.6	39.2
13:00	50.1	58.9	62.3	59.4	51.0	39.2
14:00	51.4	61.1	64.7	61.4	52.3	39.3
15:00	54.2	65.7	69.5	65.6	55.2	39.5
16:00	60.3	74.8	78.7	73.8	61.2	40.0
17:00	76.5				76.8	41.5
18:00						
19:00						
20:00						

Appendix K

PV length of 0.68 m

Figure K.1: Jan-21, PV length: 0.68 m

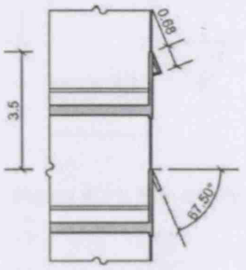


Figure K.2: Feb-21, PV length: 0.68 m

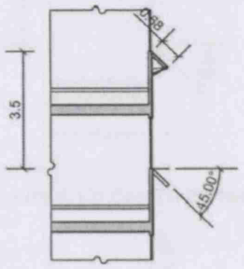


Figure K.3: March-21, PV length: 0.68 m

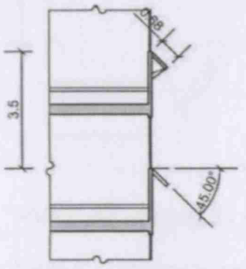


Figure K.4: Apr-21, PV length: 0.68 m

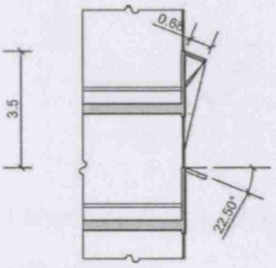


Figure K.5: May-21, PV length: 0.68 m

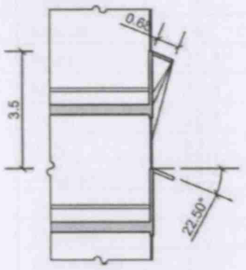


Figure K.6: Jun-21, PV length: 0.68 m

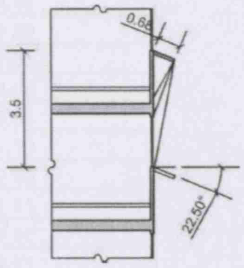


Figure K.7: Jul-21, PV length: 0.68 m

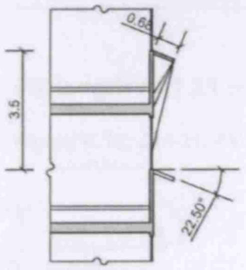


Figure K.8: Aug-21, PV length: 0.68 m

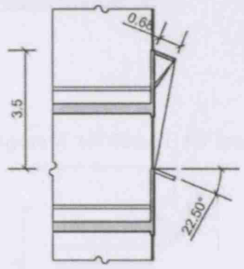


Figure K.9: Sep-21, PV length: 0.68 m

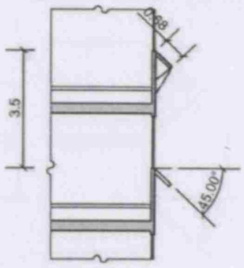


Figure K.10: Oct-21, PV length: 0.68 m

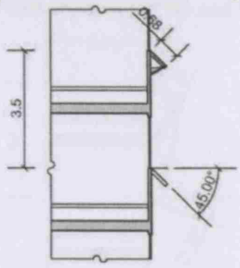


Figure K.11: Nov-21, PV length: 0.68 m

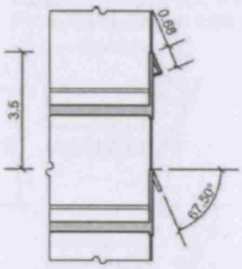
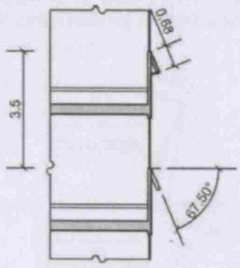


Figure K.12: Dec-21, PV length: 0.68 m



PVs 0.68 m long do not shade each others at all; table K.1 shows its energy output.

Table K.1: Electricity generated by a 4.08 m^2 (0.68 m*6 m) PV panel (12% efficiency)

Month	Tilt	Solar irradiation (kWh/m²)	Electricity generated (kWh)
January	67.5°	30.07	14.72
February	45°	49.28	24.13
March	45°	87.42	42.80
April	22.5°	106.20	52.00
May	22.5°	140.12	68.60
June	22.5°	155.40	76.08
July	22.5°	145.39	71.18
August	22.5°	128.65	62.99
September	45°	104.40	51.11
October	45°	73.47	35.97
November	67.5°	46.50	22.77
December	67.5°	29.45	14.42
Year	Various	1096.35	536.77

PV length of 1.21 m

Figure K.13: Jan-21, PV length: 1.21 m

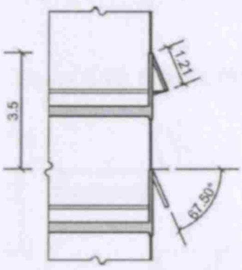


Figure K.14: Feb-21, PV length: 1.21 m

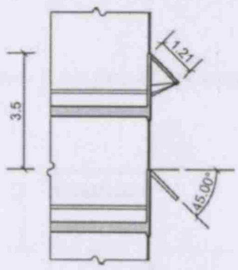


Figure K.15: March-21, PV length: 1.21 m

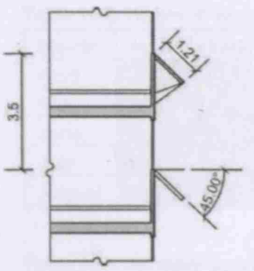


Figure K.16: April-21, PV length: 1.21 m
PV self-shading at 7:00 and 17:00

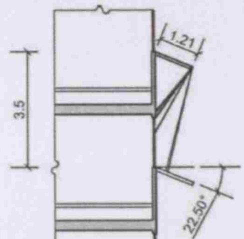


Figure K.17: May-21, PV length: 1.21 m
PV self-shading at 8:00 and 16:00

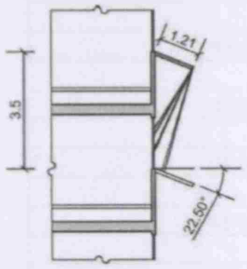


Figure K.18: Jun-21, PV length: 1.21 m
PV self-shading at 8:00 and 16:00

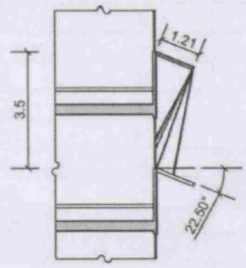


Figure K.19: Jul-21, PV length: 1.21 m
PV self-shading at 8:00 and 16:00

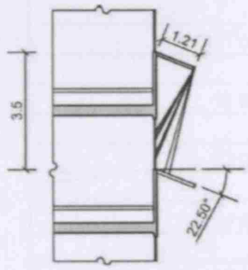


Figure K.20: Aug-21, PV length: 1.21 m
PV self-shading at 7:00 and 17:00

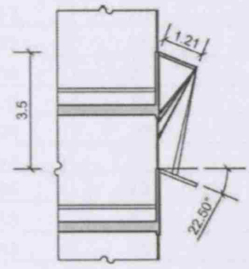


Figure K.21: Sep-21, PV length: 1.21 m

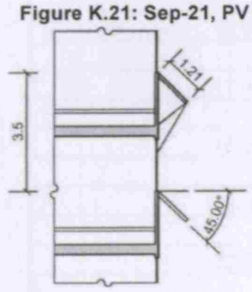


Figure K.22: Oct-21, PV length: 1.21 m

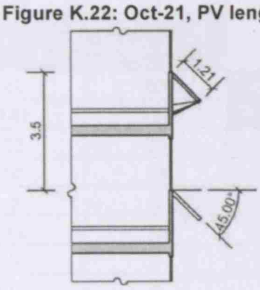


Figure K.23: Nov-21, PV length: 1.21 m

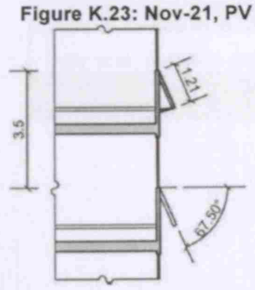


Figure K.24: Dec-21, PV length: 1.21 m

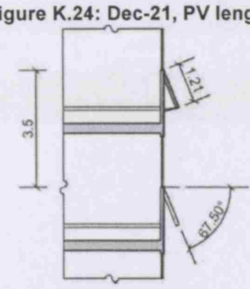


Table K.2 shows the hours in which PVs 1.21 m long shade each others.

Table K.2: Hours in which PVs 1.21 m long shade each others

Month	Hours shaded
April	7, 17
May	8, 16
June	8, 16
July	8, 16
August	7, 17

Table K.3: Monthly solar radiation (kWh/month) considering the hours in which PVs 1.21 m long shade each others

Time		Tilt: 22.5° April	Tilt: 22.5° May	Tilt: 22.5° June	Tilt: 22.5° July	Tilt: 22.5° August
04:00	B	0	0	0	0	0
	D	0	0	6	0	0
05:00	B	0	0	0	0	0
	D	0	27	42	35	8
06:00	B	5	19	33	22	10
	D	36	74	92	83	55
07:00	B	41	63	89	68	52
	D	86	127	142	136	110
08:00	B	91	117	151	120	106
	D	135	179	191	188	163
09:00	B	140	169	208	171	159
	D	177	223	232	231	209
10:00	B	179	212	258	215	202
	D	209	255	263	264	240
11:00	B	205	241	292	243	233
	D	232	279	286	287	265
12:00	B	214	251	303	254	244
	D	240	288	294	296	273
13:00	B	205	241	292	243	233
	D	232	279	286	287	265
14:00	B	179	212	258	215	202
	D	209	255	263	264	240
15:00	B	140	169	208	171	159
	D	177	223	232	231	209
16:00	B	91	117	151	120	106
	D	135	179	191	188	163
17:00	B	41	63	89	68	52
	D	86	127	142	136	110
18:00	B	5	19	33	22	10
	D	36	74	92	83	55
19:00	B	0	0	0	0	0
	D	0	27	42	35	8
20:00	B	0	0	0	0	0
	D	0	0	6	0	0
All solar radiation (Wh/m^2)		3526	4509	5167	4676	4141
Shaded (Wh/m^2)		254	592	684	616	324
Daily solar radiation (Wh/m^2)		3272 (3526-254)	3917 (4509-592)	4483 (5167-684)	4060 (4676-616)	3817 (4141-324)
Monthly solar radiation (kWh/m^2)		98.16 ((3272*30)/1000)	121.43 ((3917*31)/1000)	134.49 ((4483*30)/1000)	125.86 ((4060*31)/1000)	118.33 ((3817*31)/1000)

Table K.4: Electricity generated by a 7.26 m² (1.21 m*6 m) PV panel (12% efficiency)

Month	Tilt	Solar irradiation (kWh/m²)	Electricity generated (kWh)
January	67.5°	30.07	26.20
February	45°	49.28	42.93
March	45°	87.42	76.16
April	22.5°	98.16	85.52
May	22.5°	121.43	105.79
June	22.5°	134.49	117.17
July	22.5°	125.86	109.65
August	22.5°	118.33	103.09
September	45°	104.40	90.95
October	45°	73.47	64.01
November	67.5°	46.50	40.51
December	67.5°	29.45	25.66
Year	Various	1018.86	887.63

PV length of 1.82 m

Figure K.25: Jan-21, PV length: 1.82 m

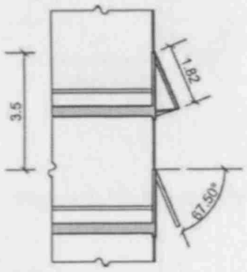


Figure K.26: Feb-21, PV length: 1.82 m

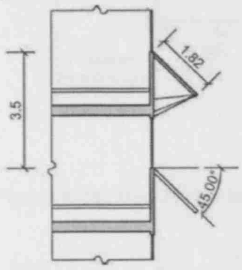


Figure K.27: March-21, PV length: 1.82 m

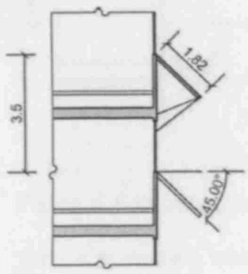


Figure K.28: April-21, PV length: 1.82 m
PV self-shading at 7:00, 8:00, 16:00 and 17:00

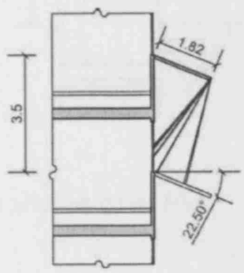


Figure K.29: May-21, PV length: 1.82 m
PV self-shading at 8:00, 9:00, 10:00, 14:00, 15:00 and 16:00

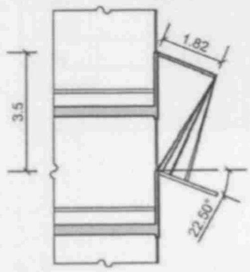


Figure K.30: Jun-21, PV length: 1.82 m
PV self-shading all the time

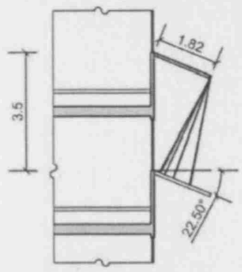


Figure K.31: Jul-21, PV length: 1.82 m
PV self-shading all the time except 12:00

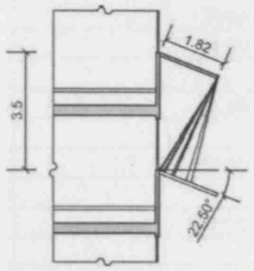


Figure K.32: Aug-21, PV length: 1.82 m
PV self-shading at 7:00, 8:00, 16:00 and 17:00

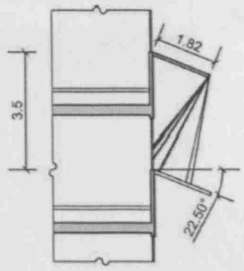


Figure K.33: Sep-21, PV length: 1.82 m
PV self-shading at 6:00

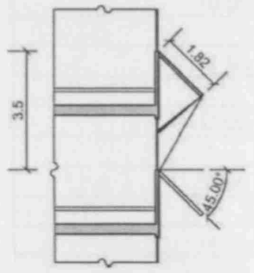


Figure K.34: Oct-21, PV length: 1.82 m

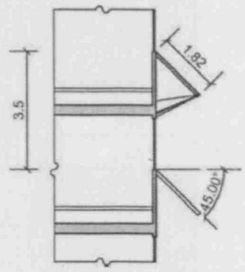


Figure K.35: Nov-21, PV length: 1.82 m

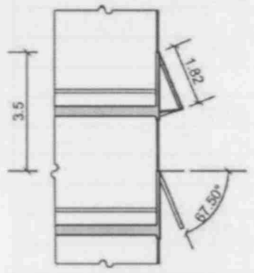


Figure K.36: Dec-21, PV length: 1.82 m

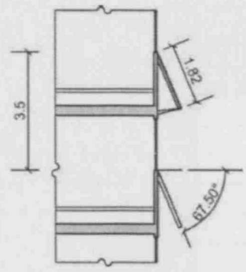


Table K.5 shows the hours in which the PV length of 1.82 m shades other PVs.

Table K.5: Hours in which PVs 1.82 m long shade each others

Month	Hours shaded
April	7, 8, 16, 17
May	8, 9, 10, 14, 15, 16
June	Shaded all the time
July	All the time except from 12
August	7, 8, 16, 17
September	Shaded at 6

Table K.6: Monthly solar radiation (kWh/month) considering the hours in which PVs 1.82 m long shade each others

Time		Tilt: 22.5˚ April	Tilt: 22.5˚ May	Tilt: 22.5˚ June	Tilt: 22.5˚ July	Tilt: 22.5˚ August	Tilt: 45˚ September
04:00	B	0	0	0	0	0	0
	D	0	0	6	0	0	0
05:00	B	0	0	0	0	0	0
	D	0	27	42	35	8	0
06:00	B	5	19	33	22	10	0
	D	36	74	92	83	55	12
07:00	B	41	63	89	68	52	35
	D	86	127	142	136	110	64
08:00	B	91	117	151	120	106	98
	D	135	179	191	188	163	113
09:00	B	140	169	208	171	159	162
	D	177	223	232	231	209	155
10:00	B	179	212	258	215	202	215
	D	209	255	263	264	240	186
11:00	B	205	241	292	243	233	249
	D	232	279	286	287	265	207
12:00	B	214	251	303	254	244	261
	D	240	288	294	296	273	215
13:00	B	205	241	292	243	233	249
	D	232	279	286	287	265	207
14:00	B	179	212	258	215	202	215
	D	209	255	263	264	240	186
15:00	B	140	169	208	171	159	162
	D	177	223	232	231	209	155
16:00	B	91	117	151	120	106	98
	D	135	179	191	188	163	113
17:00	B	41	63	89	68	52	35
	D	86	127	142	136	110	64
18:00	B	5	19	33	22	10	0
	D	36	74	92	83	55	12
19:00	B	0	0	0	0	0	0
	D	0	27	42	35	8	0
20:00	B	0	0	0	0	0	0
	D	0	0	6	0	0	0
All solar radiation (Wh/m^2)		3526	4509	5167	4676	4141	3468
Shaded (Wh/m^2)		706	2310	5167	4126	862	12
Daily solar radiation (Wh/m^2)		2820 (3526-706)	2199 (4509-2310)	0 (5167-5167)	550 (4676-4126)	3279 (4141-826)	3456 (3468-12)
Monthly solar radiation (kWh/m^2)		84.60 ((2820*30)/1000)	68.17 ((2199*31)/1000)	0.00 ((0*30)/1000)	17.05 ((550*31)/1000)	101.65 ((3279*31)/1000)	103.68 ((3456*30)/1000)

Table K.7: Electricity generated by a 10.92 m^2 (1.82 m*6 m) PV panel (12% efficiency)

Month	Tilt	Solar irradiation (kWh/m^2)	Electricity generated (kWh)
January	67.5˚	30.07	39.40
February	45˚	49.28	64.58
March	45˚	87.42	114.56
April	22.5˚	84.60	110.86
May	22.5˚	68.17	89.33
June	22.5˚	0.00	0.00
July	22.5˚	17.05	22.34
August	22.5˚	101.65	133.20
September	45˚	103.68	135.86
October	45˚	73.47	96.28
November	67.5˚	46.50	60.93
December	67.5˚	29.45	38.59
Year	Various	691.34	905.93

Appendix L

PV length of 1.60 m

Figure L.1: Jan-21, PV length: 1.60 m

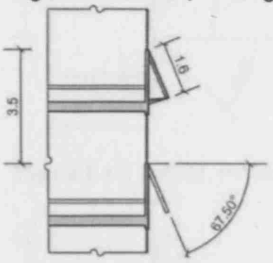


Figure L.2: Feb-21, PV length: 1.60 m

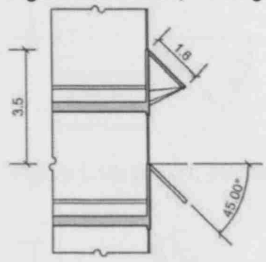


Figure L.3: March-21, PV length: 1.60 m

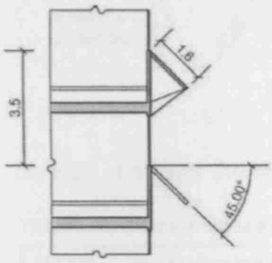


Figure L.4: Apr-21, PV length: 1.60 m
PV self-shading at 7:00 and 17:00

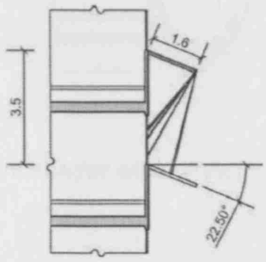


Figure L.5: May-21, PV length: 1.60 m
PV self-shading at 8:00, 9:00, 15:00 and 16:00

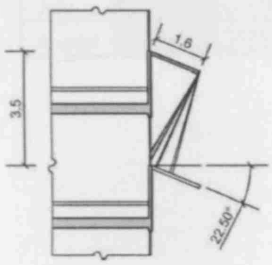


Figure L.6: Jun-21, PV length: 1.60 m
PV self-shading at 8:00, 9:00, 10:00, 14:00, 15:00 and 16:00

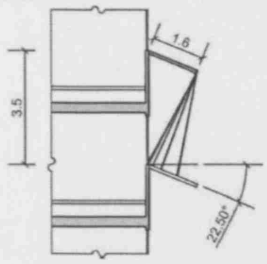


Figure L.7: Jul-21, PV length: 1.60 m
PV self-shading at 8:00, 9:00, 15:00 and 16:00

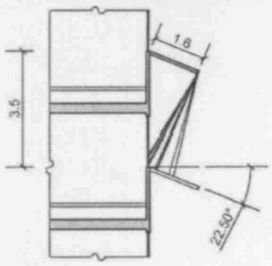


Figure L.8: Aug-21, PV length: 1.60 m
PV self-shading at 7:00 and 17:00

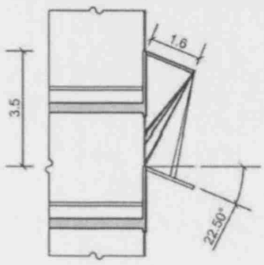


Figure L.9: Sep-21, PV length: 1.60 m

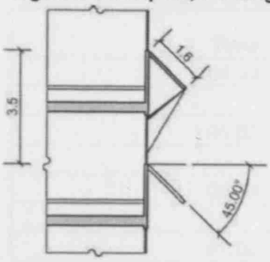


Figure L.10: Oct-21, PV length: 1.60 m

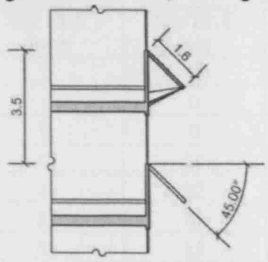


Figure L.11: Nov-21, PV length: 1.60 m

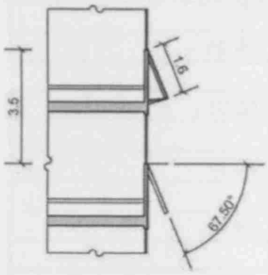


Figure L.12: Dec-21, PV length: 1.60 m

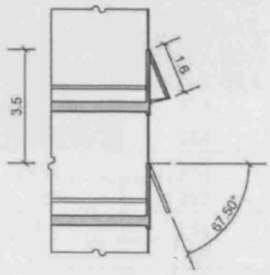


Table L.1 shows the hours in which the PV length of 1.60 m shades other PVs.

Table L.1: Hours in which PVs 1.60 m long shade each others

Month	Hours shaded
April	7, 17
May	8, 9, 15, 16
June	8, 9, 10, 14, 15, 16
July	8, 9, 15, 16
August	7, 17

Table L.2: Monthly solar radiation (kWh/month) considering the hours in which PVs 1.60 m long shade each others

Time		Tilt: 22.5° April	Tilt: 22.5° May	Tilt: 22.5° June	Tilt: 22.5° July	Tilt: 22.5° August
04:00	B	0	0	0	0	0
	D	0	0	6	0	0
05:00	B	0	0	0	0	0
	D	0	27	42	35	8
06:00	B	5	19	33	22	10
	D	36	74	92	83	55
07:00	B	41	63	89	68	52
	D	86	127	142	136	110
08:00	B	91	117	151	120	106
	D	135	179	191	188	163
09:00	B	140	169	208	171	159
	D	177	223	232	231	209
10:00	B	179	212	258	215	202
	D	209	255	263	264	240
11:00	B	205	241	292	243	233
	D	232	279	286	287	265
12:00	B	214	251	303	254	244
	D	240	288	294	296	273
13:00	B	205	241	292	243	233
	D	232	279	286	287	265
14:00	B	179	212	258	215	202
	D	209	255	263	264	240
15:00	B	140	169	208	171	159
	D	177	223	232	231	209
16:00	B	91	117	151	120	106
	D	135	179	191	188	163
17:00	B	41	63	89	68	52
	D	86	127	142	136	110
18:00	B	5	19	33	22	10
	D	36	74	92	83	55
19:00	B	0	0	0	0	0
	D	0	27	42	35	8
20:00	B	0	0	0	0	0
	D	0	0	6	0	0
All solar radiation (Wh/m^2)		3526	4509	5167	4676	4141
Shaded (Wh/m^2)		254	1376	2606	1420	324
Daily solar radiation (Wh/m^2)		3272 (3526-254)	3133 (4509-1376)	2561 (5167-2606)	3256 (4676-1420)	3817 (4141-324)
Monthly solar radiation (kWh/m^2)		98.16 ((3272*30)/1000)	97.12 ((3133*31)/1000)	76.83 ((2561*30)/1000)	100.94 ((3256*31)/1000)	118.33 ((3817*31)/1000)

Table L.3: Electricity generated by a 9.60 m^2 (1.60 m*6 m) PV panel (12% efficiency)

Month	Tilt	Solar irradiation (kWh/m²)	Electricity generated (kWh)
January	67.5°	30.07	34.64
February	45°	49.28	56.77
March	45°	87.42	100.71
April	22.5°	98.16	113.08
May	22.5°	97.12	111.88
June	22.5°	76.83	88.51
July	22.5°	100.94	116.28
August	22.5°	118.33	136.32
September	45°	104.40	120.27
October	45°	73.47	84.64
November	67.5°	46.50	53.57
December	67.5°	29.45	33.93
Year	Various	911.97	1050.59

Appendix M

As an illustration, following figures present 6 proposed PV positions and two glazed area during June.

Figure M.1: Option 1, 40% glazing area

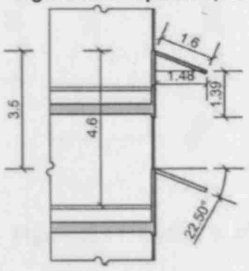


Figure M.2: Option 2, 40% glazing area

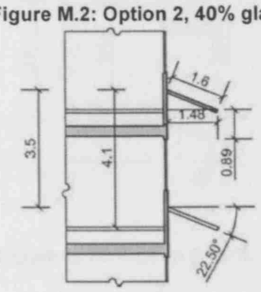


Figure M.3: Option 3, 40% glazing area

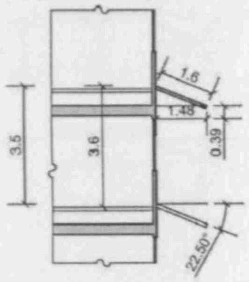


Figure M.4: Option 4, 40% glazing area

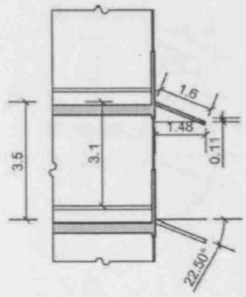


Figure M.5: Option 5, 40% glazing area

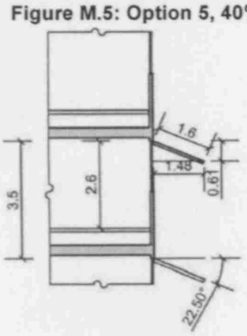


Figure M.6: Option 6, 40% glazing area

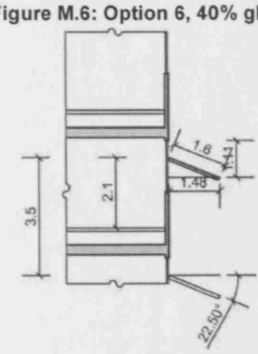


Figure M.7: Option 1, 80% glazing area

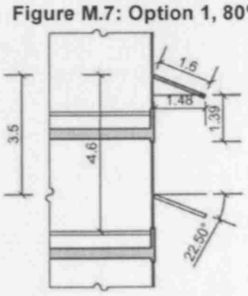


Figure M.8: Option 2, 80% glazing area

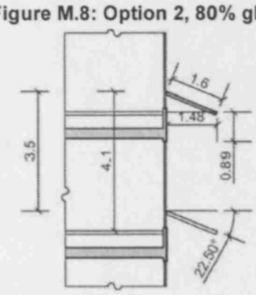


Figure M.9: Option 3, 80% glazing area

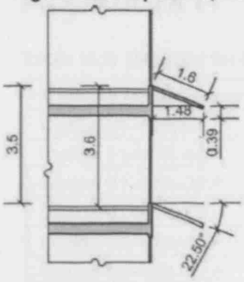


Figure M.10: Option 4, 80% glazing area

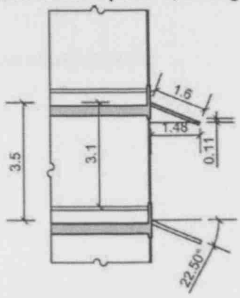


Figure M.11: Option 5, 80% glazing area

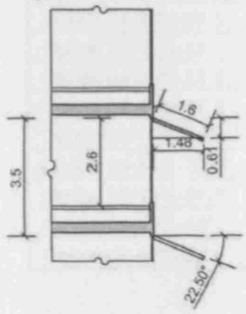
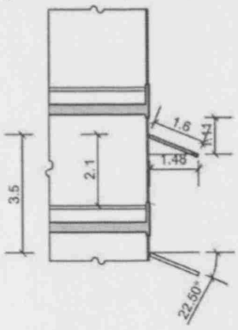


Figure M.12: Option 6, 80% glazing area



Appendix N

Table N.1: Daylight factor of different PV positions (40% glazed area on south façade)

Options (Option number, Glazing area, Tilt)	Daylight Factor
Option 01-40%-67.5°	5.49
Option 01-40%-45°	5.29
Option 01-40%-22.5°	5.35
Option 02-40%-67.5°	4.92
Option 02-40%-45°	4.84
Option 02-40%-22.5°	5.04
Option 03-40%-67.5°	4.12
Option 03-40%-45°	4.21
Option 03-40%-22.5°	4.57
Option 04-40%-67.5°	3.35
Option 04-40%-45°	3.62
Option 04-40%-22.5°	3.97
Option 05-40%-67.5°	3.08
Option 05-40%-45°	3.28
Option 05-40%-22.5°	3.59
Option 06-40%-67.5°	4.00
Option 06-40%-45°	4.10
Option 06-40%-22.5°	4.21

Table N.2: Daylight factor of different PV positions (80% glazed area on south façade)

Options (Option number, Glazing area, Tilt)	Daylight Factor
Option 01-80%-67.5°	5.56
Option 01-80%-45°	5.45
Option 01-80%-22.5°	5.56
Option 02-80%-67.5°	5.59
Option 02-80%-45°	5.52
Option 02-80%-22.5°	5.71
Option 03-80%-67.5°	4.89
Option 03-80%-45°	4.98
Option 03-80%-22.5°	5.33
Option 04-80%-67.5°	4.12
Option 04-80%-45°	4.36
Option 04-80%-22.5°	4.77
Option 05-80%-67.5°	3.48
Option 05-80%-45°	3.78
Option 05-80%-22.5°	4.20
Option 06-80%-67.5°	4.15
Option 06-80%-45°	4.22
Option 06-80%-22.5°	4.48

Appendix O

In order to design electrical lighting, first fluorescent T8 36 W tubes is used, each luminaire has 2 lamps and in total there are 15 luminaires with total load of 1140 W, and lighting power density (LPD) of 14 W/m^2. But CIBSE guide A (Humphreys et al 2006, p.6-2) recommends that the maximum lighting gain in an office building in city centre with 10 m^2 per occupants should not be more than 12 W/m^2. So it is proposed to redesign the electrical lighting, in the second design a twin 54 W T5 fluorescent luminaire is selected, the light fitting is a different type and uses a T5 lamps which are a smaller diameter more efficient (higher efficacy). This time only 8 luminaires are needed, the total circuit is now only 944 W with an LPD of just over 11.60 W/m^2.

Figure O.1: First electrical lighting design

Room Estimator - Layout 1

Luminaire

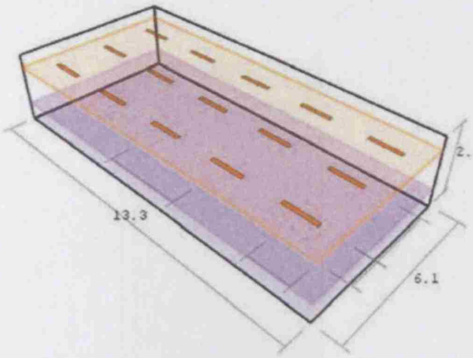
IES Filename: zlf2
Description: 2 x 36w T8 Fluorescent Indirect/Direct Luminaire

Sample data

Number of Lamps:	2	
Lamp Lumens:	3350	lms
Total Luminaire Wattage:	76	W
Light Loss Factor (LLF):	**0.855**	

Room Dimensions

Length (X):	6.1	m
Width (Y):	13.3	m
Height (Z):	2.7	m
Workplane Height:	0.7	m
Suspension Length:	0.5	m
Room Cavity Ratio (RCR):	1.793	



Room Reflectance

Ceiling:	0.70
Walls:	0.50
Floor:	0.20
Effective Ceiling Cavity:	0.626
Effective Floor Cavity:	0.193
Coeffecient of Utilization (CU):	**0.565**

Results

Estimated Average Illuminance:	**598**	**lux**
Number of Luminaires:	**15**	
Lighting Power Density (LPD):	**14.052**	**W/m^2**

Layout

	Rows (Width, Y)		Columns (Length, X)	
Grid Layout (Size):	5	×	3	luminaires
Grid Spacing:	2.66	×	2.03	m
Wall (Start) Spacing:	1.33	×	1.02	m
Ceiling Grid Spacing:	N.A.	×	N.A.	m
Spacing Criteria:	N.A.	×	N.A.	m

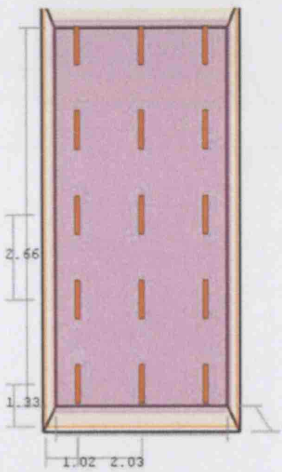


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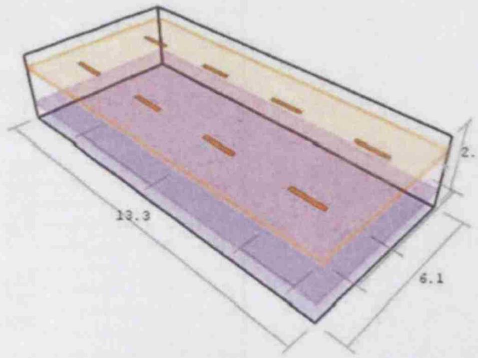
Figure O.2: Final electrical lighting design

Room Estimator - Layout 2

Luminaire

IES Filename:	zlf3	
Description:	2 x 54w T5 Fluorescent Direct/Indirect Luminaire	
Number of Lamps:	2	
Lamp Lumens:	5000	lms
Total Luminaire Wattage:	118	W
Light Loss Factor (LLF):	**0.855**	

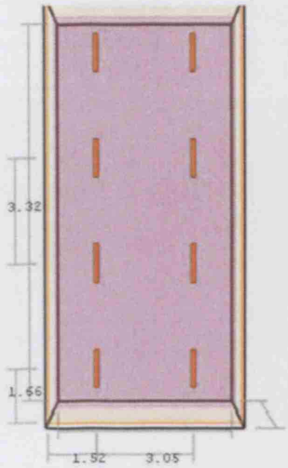
Room Dimensions



Length (X):	6.1	m
Width (Y):	13.3	m
Height (Z):	2.7	m
Workplane Height:	0.7	m
Suspension Length:	0.5	m
Room Cavity Ratio (RCR):	1.793	

Room Reflectance

Ceiling:	0.70
Walls:	0.50
Floor:	0.20
Effective Ceiling Cavity:	0.626
Effective Floor Cavity:	0.193
Coeffecient of Utilization (CU):	**0.629**



Results

Estimated Average Illuminance:	**530**	**lux**
Number of Luminaires:	**8**	
Lighting Power Density (LPD):	**11.636**	**W/m^2**

Layout

	Rows (Width, Y)		Columns (Length, X)	
Grid Layout (Size):	4	×	2	luminaires
Grid Spacing:	3.32	×	3.05	m
Wall (Start) Spacing:	1.66	×	1.52	m
Ceiling Grid Spacing:	N.A.	×	N.A.	m
Spacing Criteria:	1.3	×	1.1	m

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Figure O.3: Comparison of first and final electrical lighting designs

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Room Estimator - Comparison

Layout :	Layout 1	Layout 2	Layout 3	Units
Description :				
Summary				
Estimated Average Illuminance :	598	530		lux
Number of Luminaires :	15	8		
Lighting Power Density (LPD) :	14.052	11.636		W/m^2
Luminaire				
Label :	zl#2	zl#3		
Description :	2 x 36w T8 Fluoresc	2 x 54w T5 Fluoresc		
Lamp Lumens :	3350	5000		lms
Number of Lamps :	2	2		
Total Luminaire Watts :	76	118		W
Luminaire Rotation :	90	90		deg
Light Loss Factor (LLF) :	0.855	0.855		
Room				
Length (X) × Width (Y) × Height (Z) :	6.1 × 13.3 × 2.7	6.1 × 13.3 × 2.7		m
Workplane Height :	0.7	0.7		m
Luminaire Suspension Length :	0.5	0.5		m
Room Cavity Ratio (RCR) :	1.793	1.793		
Reflectance				
Ceiling, Walls, Floor :	0.70, 0.50, 0.20	0.70, 0.50, 0.20		
Effective Cavity Reflectance (Ceiling, Floor) :	0.626, 0.193	0.626, 0.193		
Coefficient of Utilization (CU) :	0.565	0.629		
Luminaire Layout				
Rows (width) × Columns (length) :	5 × 3	4 × 2		
Spacing (width) × (length) :	2.66 × 2.033	3.325 × 3.05		m
Wall Spacing (width) × (length) :	1.33 × 1.017	1.662 × 1.525		m
Ceiling Grid Size (width) × (length) :				m
Spacing Criteria (width) × (length) :	N.A. × N.A.	1.1 × 1.3		

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Appendix P

CO_2 emissions related to heating and cooling calculated here are the CO_2 emission associated with the required energy calculated in TAS and are not that of delivered energy. Cells in grey colour present the options which result in the minimum energy requirements and CO_2 emission and the ones in orange show the maximums. (Option 01-40 illustrates PV position option 1, and 40% glazed area).

Table P.1: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in January, PV tilt: 67.5°

Options	Heating (kWh/m²)	Cooling (kWh/m²)	Lighting (kWh/m²)	Total gas*1 (kWh/m²)	Total electricity*2 (kWh/m²)	Gas CO_2 emission*3 ($kgCO_2/m^2$)	Electricity CO_2 emission*4 ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	0.69	0.00	1.29	0.66	1.29	0.13	0.67	0.80
02-40	0.69	0.00	1.38	0.66	1.38	0.13	0.72	0.85
03-40	0.72	0.00	1.52	0.69	1.52	0.14	0.79	0.93
04-40	0.74	0.00	1.70	0.71	1.70	0.14	0.88	1.02
05-40	0.77	0.00	1.78	0.74	1.78	0.15	0.93	1.07
06-40	0.88	0.00	1.55	0.84	1.55	0.17	0.81	0.97
01-80	0.90	0.00	1.28	0.71	1.28	0.17	0.67	0.84
02-80	0.80	0.00	1.28	0.71	1.28	0.15	0.67	0.82
03-80	0.78	0.00	1.38	0.75	1.38	0.15	0.72	0.87
04-80	0.81	0.00	1.52	0.78	1.52	0.15	0.79	0.94
05-80	0.85	0.00	1.67	0.82	1.67	0.16	0.87	1.03
06-80	0.95	0.00	1.52	0.99	1.52	0.18	0.79	0.97

*1 Total gas: Heating
*2 Total Electricity: Cooling and Lighting
*3 Gas CO_2 emission factors: 0.19 $kgCO_2/kWh$ (Anon, 2003a)
*4 Electricity CO_2 emission factors: 0.52 $kgCO_2/kWh$ (Anon, 2003a)

Table P.2: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in February, PV tilt: 45°

Options	Heating (kWh/m²)	Cooling (kWh/m²)	Lighting (kWh/m²)	Total gas (kWh/m²)	Total electricity (kWh/m²)	Gas CO_2 emission ($kgCO_2/m^2$)	Electricity CO_2 emission ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	1.10	0.00	0.55	1.05	0.55	0.21	0.29	0.50
02-40	1.12	0.00	0.59	1.06	0.59	0.21	0.31	0.52
03-40	1.22	0.00	0.65	1.16	0.65	0.23	0.34	0.57
04-40	1.35	0.00	0.73	1.29	0.73	0.26	0.38	0.64
05-40	1.46	0.00	0.79	1.39	0.79	0.28	0.41	0.69
06-40	1.58	0.00	0.66	1.51	0.66	0.30	0.34	0.64
01-80	1.39	0.00	0.54	1.06	0.54	0.26	0.28	0.54
02-80	1.22	0.00	0.54	1.08	0.54	0.23	0.28	0.51
03-80	1.23	0.00	0.58	1.17	0.58	0.23	0.30	0.54
04-80	1.36	0.00	0.63	1.30	0.63	0.26	0.33	0.59
05-80	1.50	0.00	0.70	1.43	0.70	0.29	0.36	0.65
06-80	1.59	0.00	0.64	1.70	0.64	0.30	0.33	0.63

Table P.3: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in March, PV tilt: 45°

Options	Heating (kWh/m²)	Cooling (kWh/m²)	Lighting (kWh/m²)	Total gas (kWh/m²)	Total electricity (kWh/m²)	Gas CO_2 emission ($kgCO_2/m^2$)	Electricity CO_2 emission ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	1.44	0.00	0.66	1.36	0.66	0.27	0.34	0.62
02-40	1.52	0.00	0.70	1.44	0.70	0.29	0.36	0.65
03-40	1.65	0.00	0.78	1.57	0.78	0.31	0.41	0.72
04-40	1.79	0.00	0.87	1.70	0.87	0.34	0.45	0.79
05-40	1.86	0.00	0.93	1.77	0.93	0.35	0.48	0.84
06-40	2.00	0.00	0.79	1.91	0.79	0.38	0.41	0.79
01-80	1.84	0.00	0.65	1.36	0.65	0.35	0.34	0.69
02-80	1.59	0.00	0.64	1.44	0.64	0.30	0.33	0.63
03-80	1.67	0.00	0.69	1.59	0.69	0.32	0.36	0.68
04-80	1.85	0.00	0.76	1.77	0.76	0.35	0.40	0.75
05-80	2.02	0.00	0.84	1.94	0.84	0.38	0.44	0.82
06-80	2.13	0.00	0.78	2.24	0.78	0.40	0.41	0.81

Table P.4: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in April, PV tilt: 22.5°

Options	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total gas*1 (kWh/m^2)	Total electricity*2 (kWh/m^2)	Gas CO_2 emission*3 ($kgCO_2/m^2$)	Electricity CO_2 emission*4 ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	0.45	0.03	0.10	0.44	0.13	0.09	0.07	0.15
02-40	0.50	0.01	0.11	0.49	0.12	0.10	0.06	0.16
03-40	0.57	0.00	0.13	0.56	0.13	0.11	0.07	0.18
04-40	0.65	0.00	0.16	0.62	0.16	0.12	0.08	0.21
05-40	0.71	0.00	0.19	0.69	0.19	0.13	0.10	0.23
06-40	0.79	0.00	0.15	0.76	0.15	0.15	0.08	0.23
01-80	0.52	0.03	0.09	0.37	0.12	0.10	0.06	0.16
02-80	0.42	0.07	0.09	0.41	0.16	0.08	0.08	0.16
03-80	0.49	0.04	0.10	0.48	0.14	0.09	0.07	0.17
04-80	0.58	0.01	0.12	0.56	0.13	0.11	0.07	0.18
05-80	0.69	0.00	0.15	0.67	0.15	0.13	0.08	0.21
06-80	0.69	0.00	0.13	0.68	0.13	0.13	0.07	0.20

*1 Total gas: Heating
*2 Total Electricity: Cooling and Lighting
*3 Gas CO_2 emission factors: 0.19 $kgCO_2/kWh$ (Anon, 2003a)
*4 Electricity CO_2 emission factors: 0.52 $kgCO_2/kWh$ (Anon, 2003a)

Table P.5: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in May, PV tilt: 22.5°

Options	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total gas (kWh/m^2)	Total electricity (kWh/m^2)	Gas CO_2 emission ($kgCO_2/m^2$)	Electricity CO_2 emission ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	0.08	1.21	0.01	0.07	1.22	0.02	0.63	0.65
02-40	0.10	1.08	0.02	0.10	1.10	0.02	0.57	0.59
03-40	0.13	0.96	0.03	0.12	0.99	0.02	0.51	0.54
04-40	0.16	0.84	0.05	0.16	0.89	0.03	0.46	0.49
05-40	0.20	0.71	0.07	0.20	0.78	0.04	0.41	0.44
06-40	0.25	0.57	0.04	0.24	0.61	0.05	0.32	0.36
01-80	0.07	1.39	0.01	0.03	1.40	0.01	0.73	0.74
02-80	0.04	1.77	0.01	0.05	1.78	0.01	0.93	0.93
03-80	0.07	1.36	0.01	0.07	1.37	0.01	0.71	0.73
04-80	0.12	1.11	0.02	0.11	1.13	0.02	0.59	0.61
05-80	0.18	0.89	0.04	0.17	0.93	0.03	0.48	0.52
06-80	0.16	0.95	0.03	0.17	0.98	0.03	0.51	0.54

Table P.6: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in June, PV tilt: 22.5°

Options	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total gas (kWh/m^2)	Total electricity (kWh/m^2)	Gas CO_2 emission ($kgCO_2/m^2$)	Electricity CO_2 emission ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	0.00	3.25	0.02	0.00	3.27	0.00	1.70	1.70
02-40	0.00	3.16	0.02	0.00	3.18	0.00	1.65	1.65
03-40	0.00	3.05	0.03	0.00	3.08	0.00	1.60	1.60
04-40	0.01	2.89	0.05	0.01	2.94	0.00	1.53	1.53
05-40	0.01	2.70	0.07	0.01	2.77	0.00	1.44	1.44
06-40	0.02	2.50	0.04	0.01	2.54	0.00	1.32	1.32
01-80	0.00	3.59	0.02	0.00	3.61	0.00	1.88	1.88
02-80	0.00	4.01	0.02	0.00	4.03	0.00	2.10	2.10
03-80	0.00	3.48	0.02	0.00	3.50	0.00	1.82	1.82
04-80	0.00	3.26	0.03	0.00	3.29	0.00	1.71	1.71
05-80	0.01	3.01	0.04	0.01	3.05	0.00	1.59	1.59
06-80	0.01	3.08	0.03	0.01	3.11	0.00	1.62	1.62

Table P.7: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in July, PV tilt: 22.5°

Options	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total gas*1 (kWh/m^2)	Total electricity*2 (kWh/m^2)	Gas CO_2 emission*3 ($kgCO_2/m^2$)	Electricity CO_2 emission*4 ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	0.00	4.68	0.01	0.00	4.69	0.00	2.44	2.44
02-40	0.00	4.57	0.02	0.00	4.59	0.00	2.39	2.39
03-40	0.00	4.46	0.02	0.00	4.48	0.00	2.33	2.33
04-40	0.00	4.32	0.03	0.00	4.35	0.00	2.26	2.26
05-40	0.00	4.14	0.05	0.00	4.19	0.00	2.18	2.18
06-40	0.00	3.94	0.03	0.00	3.97	0.00	2.06	2.06
01-80	0.00	5.27	0.01	0.00	5.28	0.00	2.75	2.75
02-80	0.00	5.85	0.01	0.00	5.86	0.00	3.05	3.05
03-80	0.00	5.03	0.01	0.00	5.04	0.00	2.62	2.62
04-80	0.00	4.74	0.02	0.00	4.76	0.00	2.48	2.48
05-80	0.00	4.47	0.03	0.00	4.50	0.00	2.34	2.34
06-80	0.00	4.58	0.02	0.00	4.60	0.00	2.39	2.39

*1 Total gas: Heating
*2 Total Electricity: Cooling and Lighting
*3 Gas CO_2 emission factors: 0.19 $kgCO_2/kWh$ (Anon, 2003a)
*4 Electricity CO_2 emission factors: 0.52 $kgCO_2/kWh$ (Anon, 2003a)

Table P.8: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in August, PV tilt: 22.5°

Options	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total gas (kWh/m^2)	Total electricity (kWh/m^2)	Gas CO_2 emission ($kgCO_2/m^2$)	Electricity CO_2 emission ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	0.00	3.97	0.08	0.00	4.05	0.00	2.11	2.11
02-40	0.00	3.74	0.09	0.00	3.83	0.00	1.99	1.99
03-40	0.00	3.56	0.12	0.00	3.68	0.00	1.91	1.91
04-40	0.00	3.43	0.16	0.00	3.59	0.00	1.87	1.87
05-40	0.00	3.26	0.19	0.00	3.45	0.00	1.79	1.79
06-40	0.00	3.03	0.14	0.00	3.17	0.00	1.65	1.65
01-80	0.00	4.37	0.07	0.00	4.44	0.00	2.31	2.31
02-80	0.00	4.98	0.07	0.00	5.05	0.00	2.63	2.63
03-80	0.00	4.21	0.08	0.00	4.29	0.00	2.23	2.23
04-80	0.00	3.83	0.11	0.00	3.94	0.00	2.05	2.05
05-80	0.00	3.53	0.14	0.00	3.67	0.00	1.91	1.91
06-80	0.00	3.64	0.12	0.00	3.76	0.00	1.96	1.96

Table P.9: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in September, PV tilt: 45°

Options	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total gas (kWh/m^2)	Total electricity (kWh/m^2)	Gas CO_2 emission ($kgCO_2/m^2$)	Electricity CO_2 emission ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	0.00	1.77	0.28	0.00	2.05	0.00	1.07	1.07
02-40	0.00	1.57	0.30	0.00	1.87	0.00	0.97	0.97
03-40	0.00	1.33	0.35	0.00	1.68	0.00	0.87	0.87
04-40	0.00	1.14	0.41	0.00	1.55	0.00	0.81	0.81
05-40	0.01	1.05	0.45	0.01	1.50	0.00	0.78	0.78
06-40	0.01	0.95	0.36	0.01	1.31	0.00	0.68	0.68
01-80	0.00	1.79	0.27	0.00	2.06	0.00	1.07	1.07
02-80	0.00	2.18	0.27	0.00	2.45	0.00	1.27	1.27
03-80	0.00	1.76	0.30	0.00	2.06	0.00	1.07	1.07
04-80	0.00	1.47	0.34	0.00	1.81	0.00	0.94	0.94
05-80	0.01	1.18	0.39	0.01	1.57	0.00	0.82	0.82
06-80	0.01	1.21	0.35	0.02	1.56	0.00	0.81	0.81

Table P.10: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in October, PV tilt: 45°

Options	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total gas*1 (kWh/m^2)	Total electricity*2 (kWh/m^2)	Gas CO_2 emission*3 ($kgCO_2/m^2$)	Electricity CO_2 emission*4 ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	0.12	0.08	0.76	0.12	0.84	0.02	0.44	0.46
02-40	0.16	0.04	0.80	0.15	0.84	0.03	0.44	0.47
03-40	0.22	0.01	0.87	0.21	0.88	0.04	0.46	0.50
04-40	0.29	0.00	0.96	0.27	0.96	0.06	0.50	0.55
05-40	0.33	0.00	1.03	0.32	1.03	0.06	0.54	0.60
06-40	0.38	0.00	0.89	0.36	0.89	0.07	0.46	0.54
01-80	0.20	0.04	0.75	0.07	0.79	0.04	0.41	0.45
02-80	0.12	0.12	0.74	0.10	0.86	0.02	0.45	0.47
03-80	0.17	0.06	0.79	0.16	0.85	0.03	0.44	0.47
04-80	0.24	0.02	0.85	0.23	0.87	0.05	0.45	0.50
05-80	0.33	0.00	0.93	0.32	0.93	0.06	0.48	0.55
06-80	0.35	0.00	0.87	0.44	0.87	0.07	0.45	0.52

*1 Total gas: Heating
*2 Total Electricity: Cooling and Lighting
*3 Gas CO_2 emission factors: 0.19 $kgCO_2/kWh$ (Anon, 2003a)
*4 Electricity CO_2 emission factors: 0.52 $kgCO_2/kWh$ (Anon, 2003a)

Table P.11: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in November, PV tilt: 67.5°

Options	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total gas (kWh/m^2)	Total electricity (kWh/m^2)	Gas CO_2 emission ($kgCO_2/m^2$)	Electricity CO_2 emission ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	0.25	0.01	1.16	0.24	1.17	0.05	0.61	0.66
02-40	0.28	0.01	1.23	0.26	1.24	0.05	0.64	0.70
03-40	0.33	0.00	1.36	0.32	1.36	0.06	0.71	0.77
04-40	0.38	0.00	1.52	0.36	1.52	0.07	0.79	0.86
05-40	0.41	0.00	1.59	0.39	1.59	0.08	0.83	0.90
06-40	0.47	0.00	1.38	0.45	1.38	0.09	0.72	0.81
01-80	0.39	0.00	1.16	0.24	1.16	0.07	0.60	0.68
02-80	0.31	0.01	1.15	0.26	1.16	0.06	0.60	0.66
03-80	0.33	0.00	1.24	0.32	1.24	0.06	0.64	0.71
04-80	0.40	0.00	1.36	0.38	1.36	0.08	0.71	0.78
05-80	0.46	0.00	1.49	0.44	1.49	0.09	0.77	0.86
06-80	0.53	0.00	1.35	0.59	1.35	0.10	0.70	0.80

Table P.12: Impacts of different PV positions and glazed area on energy requirement and CO_2 emission in December, PV tilt: 67.5°

Options	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total gas (kWh/m^2)	Total electricity (kWh/m^2)	Gas CO_2 emission ($kgCO_2/m^2$)	Electricity CO_2 emission ($kgCO_2/m^2$)	Total CO_2 emission ($kgCO_2/m^2$)
01-40	0.30	0.01	1.21	0.28	1.22	0.06	0.63	0.69
02-40	0.31	0.01	1.29	0.30	1.30	0.06	0.68	0.73
03-40	0.36	0.01	1.42	0.34	1.43	0.07	0.74	0.81
04-40	0.40	0.00	1.59	0.38	1.59	0.08	0.83	0.90
05-40	0.44	0.00	1.66	0.42	1.66	0.08	0.86	0.95
06-40	0.52	0.00	1.45	0.49	1.45	0.10	0.75	0.85
01-80	0.46	0.00	1.20	0.29	1.20	0.09	0.62	0.71
02-80	0.37	0.01	1.19	0.31	1.20	0.07	0.62	0.69
03-80	0.38	0.01	1.29	0.36	1.30	0.07	0.68	0.75
04-80	0.43	0.00	1.42	0.41	1.42	0.08	0.74	0.82
05-80	0.49	0.00	1.56	0.46	1.56	0.09	0.81	0.90
06-80	0.56	0.00	1.42	0.63	1.42	0.11	0.74	0.84

Appendix Q

CO_2 emissions related to heating and cooling calculated here are the CO_2 emission associated with the required energy calculated in TAS and are not that of delivered energy.

Table Q.1: PV positions which results in the minimum energy requirement and CO_2 emission (40% glazed area)

Options (Option number, Glazed area)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total CO_2 emission * ($kgCO_2/m^2$)
January-01-40	0.69	0.00	1.29	0.80
February-01-40	1.10	0.00	0.55	0.50
March-01-40	1.44	0.00	0.66	0.62
April-01-40	0.45	0.03	0.10	0.15
May-06-40	0.25	0.57	0.04	0.36
June-06-40	0.02	2.50	0.04	1.32
July-06-40	0.00	3.94	0.03	2.06
August-06-40	0.00	3.03	0.14	1.65
September-06-40	0.01	0.95	0.36	0.68
October-01-40	0.12	0.08	0.76	0.46
November-01-40	0.25	0.01	1.16	0.66
December-01-40	0.30	0.01	1.21	0.69
Year	4.63	11.12	6.34	9.95

* Gas CO_2 emission factors: 0.19 $kgCO_2/kWh$, Electricity CO_2 emission factors: 0.52 $kgCO_2/kWh$ (Anon, 2003a)

Table Q.2: PV positions which results in the minimum energy requirement and CO_2 emission (80% glazed area)

Options (Option number, Glazed area)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total CO_2 emission ($kgCO_2/m^2$)
January-02-80	0.80	0.00	1.28	0.82
February-02-80	1.22	0.00	0.54	0.51
March-02-80	1.59	0.00	0.64	0.63
April-01-80	0.52	0.03	0.09	0.16
May-05-80	0.18	0.89	0.04	0.52
June-05-80	0.01	3.01	0.04	1.59
July-05-80	0.00	4.47	0.03	2.34
August-05-80	0.00	3.53	0.14	1.91
September-06-80	0.01	1.21	0.35	0.81
October-01-80	0.20	0.04	0.75	0.45
November-02-80	0.31	0.01	1.15	0.66
December-02-80	0.37	0.01	1.19	0.69
Year	5.21	13.20	6.24	11.09

Table Q.3: PV positions which results in the maximum energy requirement and CO_2 emission (40% glazed area)

Options (Option number, Glazed area)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total CO_2 emission ($kgCO_2/m^2$)
January-05-40	0.77	0.00	1.78	1.07
February-05-40	1.46	0.00	0.79	0.69
March-05-40	1.86	0.00	0.93	0.84
April-05-40	0.71	0.00	0.19	0.23
May-01-40	0.08	1.21	0.01	0.65
June-01-40	0.00	3.25	0.02	1.70
July-01-40	0.00	4.68	0.01	2.44
August-01-40	0.00	3.97	0.08	2.11
September-01-40	0.00	1.77	0.28	1.07
October-05-40	0.33	0.00	1.03	0.60
November-05-40	0.41	0.00	1.59	0.90
December-05-40	0.44	0.00	1.66	0.95
Year	6.06	14.88	8.37	13.25

Table Q.4: PV positions which results in the maximum energy requirement and CO_2 emission (80% glazed area)

Options (Option number, Glazed area)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total CO_2 emission * ($kgCO_2/m^2$)
January-05-80	0.85	0.00	1.67	1.03
February-05-80	1.50	0.00	0.70	0.65
March-05-80	2.02	0.00	0.84	0.82
April-05-80	0.69	0.00	0.15	0.21
May-02-80	0.04	1.77	0.01	0.93
June-02-80	0.00	4.01	0.02	2.10
July-02-80	0.00	5.85	0.01	3.05
August-02-80	0.00	4.98	0.07	2.63
September-02-80	0.00	2.18	0.27	1.27
October-05-80	0.33	0.00	0.93	0.55
November-05-80	0.46	0.00	1.49	0.86
December-05-80	0.49	0.00	1.56	0.90
Year	6.38	18.79	7.72	15.00

* Gas CO_2 emission factors: 0.19 $kgCO_2/kWh$, Electricity CO_2 emission factors: 0.52 $kgCO_2/kWh$ (Anon, 2003a)

Table Q.5: Final PV positions, internal energy requirement and CO_2 emission (80% glazed area)

Options (Option number, Glazed area)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Lighting (kWh/m^2)	Total CO_2 emission ($kgCO_2/m^2$)
January-02-80	0.80	0.00	1.28	0.82
February-02-80	1.22	0.00	0.54	0.51
March-02-80	1.59	0.00	0.64	0.63
April-02-80	0.42	0.07	0.09	0.16
May-05-80	0.18	0.89	0.04	0.52
June-05-80	0.01	3.01	0.04	1.59
July-05-80	0.00	4.47	0.03	2.34
August-05-80	0.00	3.53	0.14	1.91
September-05-80	0.01	1.18	0.39	0.82
October-02-80	0.12	0.12	0.74	0.47
November-02-80	0.31	0.01	1.15	0.66
December-02-80	0.37	0.01	1.19	0.69
Year	5.03	13.29	6.27	11.13

Appendix R

Proposed PV tilts, length and positions

Figure R.1: January

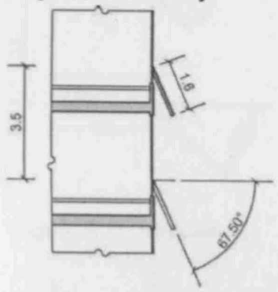


Figure R.2: February

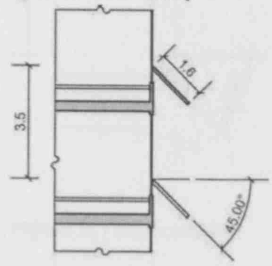


Figure R.3: March

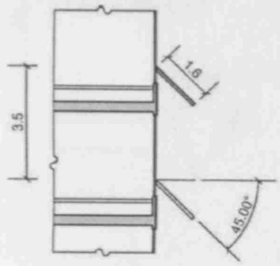


Figure R.4: April

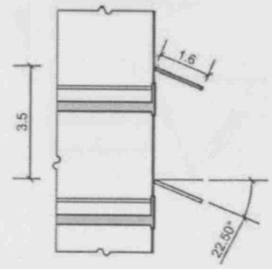


Figure R.5: May

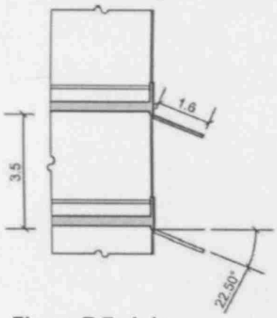


Figure R.6: June

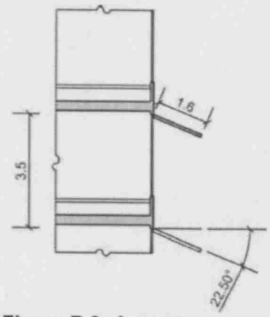


Figure R.7: July

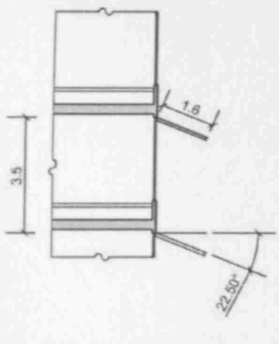


Figure R.8: August

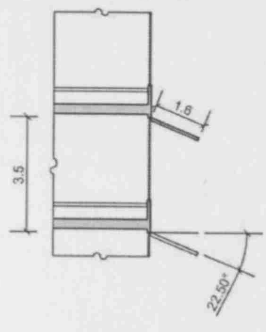


Figure R.9: September

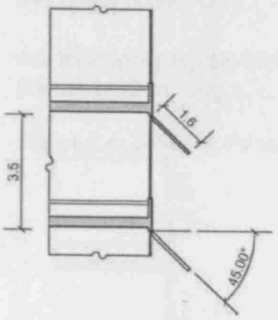


Figure R.10: October

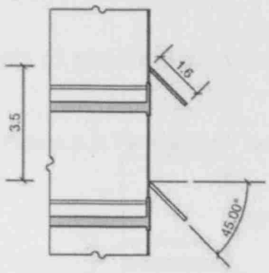


Figure R.11: November

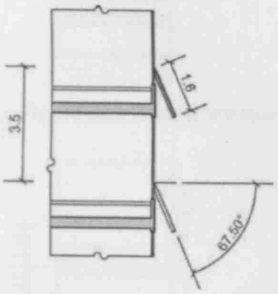
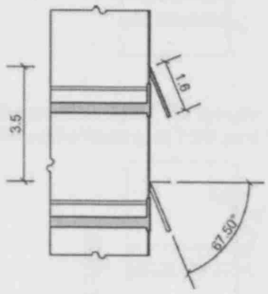


Figure R.12: December



Appendix S

As following figure show PV self-shading of louvred panels (3 panels 0.53 m long) is the same as a panel 1.60 m long.

Figure S.1: January, PV length: 0.53 m

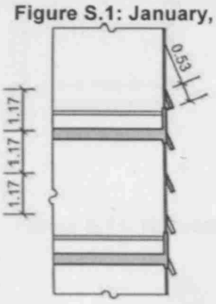


Figure S.2: February, PV length: 0.53 m

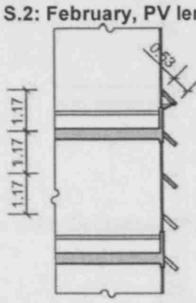


Figure S.3: March, PV length: 0.53 m

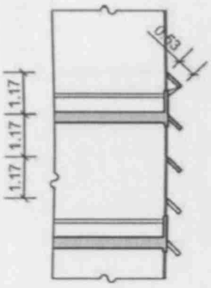


Figure S.4: April, PV length: 0.53 m
PV self-shading at 7:00 and 17:00

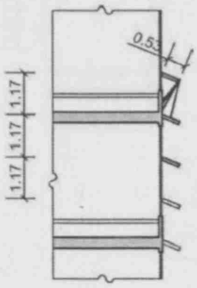


Figure S.5: May, PV length: 0.53 m
PV self-shading at 8:00 and 16:00

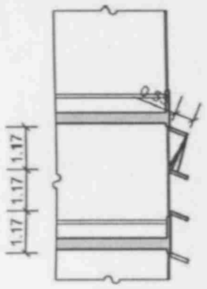


Figure S.6: June, PV length: 0.53 m
PV self-shading at 8:00 and 16:00

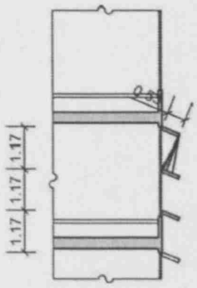


Figure S.7: July, PV length: 0.53 m
PV self-shading at 8:00 and 16:00

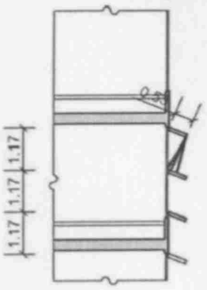


Figure S.8: August, PV length: 0.53 m
PV self-shading at 7:00 and 17:00

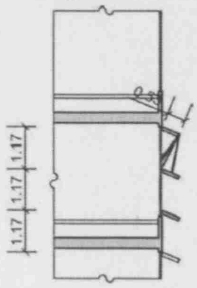


Figure S.9: September, PV length: 0.53 m

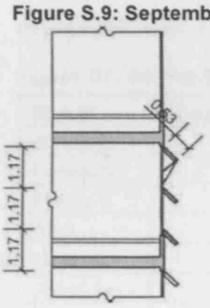


Figure S.10: October, PV length: 0.53 m

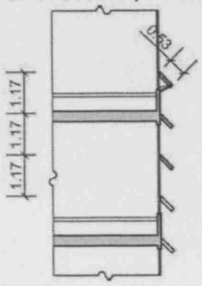


Figure S.11: November, PV length: 0.53 m

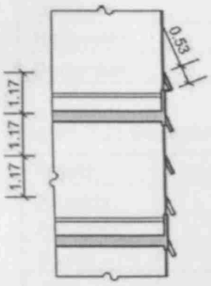
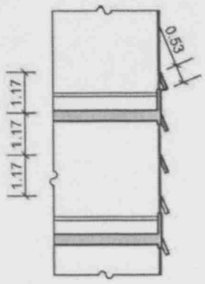


Figure S.12: December, PV length: 0.53 m



Appendix T

Figure T.1: Daylight factor, PV panel 1.60 m long

Month	Daylight Factor
January	5.77
February	5.70
March	5.70
April	5.82
May	4.68
June	4.68
July	4.68
August	4.68
September	4.32
October	5.70
November	5.77
December	5.77

Figure T.2: Daylight factor, 3 PV panels 0.53 m long

Month	Daylight Factor
January	4.94
February	5.00
March	5.00
April	5.18
May	5.04
June	5.04
July	5.04
August	5.04
September	4.86
October	5.00
November	4.94
December	4.94

Appendix U

CO_2 emission calculated here is the CO_2 emission associated with the required cooling energy calculated in TAS and is not that of delivered energy.

Table U.1: Cooling energy requirement and related CO_2 emission without night ventilation (Louvred PV with transparency of 0.50)

Month	Cooling (kWh/m²)	CO_2 emission (kgCO_2/m²)*
January-02-67.5°	0.00	0.00
February-02-45°	0.00	0.00
March-02-45°	0.00	0.00
April-02-22.5°	0.18	0.09
May-05-22.5°	2.52	1.31
June-05-22.5°	4.67	2.43
July-05-22.5°	6.50	3.38
August-05-22.5°	5.81	3.02
September-05-45°	2.93	1.52
October-02-45°	0.55	0.29
November-02-67.5°	0.00	0.00
December-02-67.5°	0.00	0.00
Year	23.16	12.04

* Electricity CO_2 emission factors: 0.52 kgCO_2/kWh (Anon, 2003a)

Table U.2: Cooling energy requirement and related CO_2 emission considering night ventilation

Month	Cooling (kWh/m²)	CO_2 emission (kgCO_2/m²)
January-02-67.5°	0.00	0.00
February-02-45°	0.00	0.00
March-02-45°	0.00	0.00
April-02-22.5°	0.10	0.05
May-05-22.5°	1.57	0.82
June-05-22.5°	3.29	1.71
July-05-22.5°	4.58	2.38
August-05-22.5°	3.55	1.85
September-05-45°	1.36	0.71
October-02-45°	0.02	0.01
November-02-67.5°	0.00	0.00
December-02-67.5°	0.00	0.00
Year	14.47	7.52

Appendix V

Energy output of PV system, using real PV system efficiencies, and solar radiation of typical London weather are calculated before (Chapter 5, p.24). It is assumed that PV is not shaded by landform, surrounding building. Probable shading due to its cladding structure is also considered as negligible. According to TAS (Chapter 5, p.32), heat recovery is only needed during 281 hours in the first fourth months of the year, so as it is assumed previously ventilation consumption is doubled when heat recovery is in use. Table V.1 presents average daily PV energy output as well as average daily ventilation and lighting consumption.
In order to calculate daily lighting consumption, based on TAS calendar, monthly consumption is divided by working days.

Table V.1: Average daily PV output, ventilation and lighting consumption

Month	Average PV electricity output over a day (kWh/day)	Average ventilation consumption (kWh/day)	Average lighting consumption (kWh/day)
January	1.12 (34.64/31)	0.49 ((27*9*2)/1000)	4.43 ((1.28*79.59)/23)
February	2.03 (56.77/28)	0.49 ((27*9*2)/1000)	2.15 ((0.54*79.59)/20)
March	3.25 (100.71/31)	0.49 ((27*9*2)/1000)	2.21 ((0.64*79.59)/23)
April	3.77 (113.08/30)	0.49 ((27*9*2)/1000)	0.36 ((0.09*79.59)/20)
May	3.61 (111.88/31)	0.24 ((27*9)/1000)	0.14 ((0.04*79.59)/23)
June	2.95 (88.51/30)	0.24 ((27*9)/1000)	0.15 ((0.04*79.59)/21)
July	3.75 (116.28/31)	0.24 ((27*9)/1000)	0.11 ((0.03*79.59)/22)
August	4.40 (136.32/31)	0.24 ((27*9)/1000)	0.48 ((0.14*79.59)/23)
September	4.01 (120.27/30)	0.24 ((27*9)/1000)	1.55 ((0.39*79.59)/20)
October	2.73 (84.64/31)	0.24 ((27*9)/1000)	2.56 ((0.74*79.59)/23)
November	1.79 (53.57/30)	0.24 ((27*9)/1000)	4.16 ((1.15*79.59)/22)
December	1.09 (33.93/31)	0.24 ((27*9)/1000)	4.51 ((1.19*79.59)/21)

As table V.2 shows the main lighting loads are in winter and the main PV energy production is in summer, any battery backup system is not going to be big enough to store energy in summer for use in winter. So daily amount of energy which can be provided by PV is calculated to find out how much of daily lighting requirement can be provided by PV power.
Cells in grey presents the days when lighting requirements can be 100% provided by PV, and the ones in orange shows when it cannot be fully provided by PV power.

Table V.2: Average daily PV output for lighting requirement

Month	Average PV energy output after providing fan requirements (kWh/day)	Average lighting consumption (kWh/day)	Average lighting requirement which can be provided by PV (kWh/day)
January	0.63 (1.12-0.49)	4.43	0.63
February	1.54 (2.03-0.49)	2.15	1.54
March	2.76 (3.25-0.49)	2.21	2.21
April	3.28 (3.77-0.49)	0.36	0.36
May	3.37 (3.61-0.24)	0.14	0.14
June	2.71 (2.95-0.24)	0.15	0.15
July	3.51 (3.75-0.24)	0.11	0.11
August	4.15 (4.40-0.24)	0.48	0.48
September	3.77 (4.01-0.24)	1.55	1.55
October	2.49 (2.73-0.24)	2.56	2.49
November	1.54 (1.79-0.24)	4.16	1.54
December	0.85 (1.09-0.24)	4.51	0.85

Lighting energy requirement for 12 representative days in a year is 22.81 kWh, and PV can provide 12.05 kWh of it, so as calculated PV can provide 53% of lighting requirements.

Appendix W

Table W.1: Annual delivered energy consumption of good practice air-conditioned office (standard type) (Anon 2003a)

Air-conditioned office (Standard)	Heating and hot water (kWh/(m^2.yr))	Cooling (kWh/(m^2.yr))	Fans, pumps and controls (kWh/(m^2.yr))
Good practice	97.00	14.00	30.00

It is assumed that 80% of delivered energy for heating and hot water is for heating, and 95% of delivered energy for fans, pumps and controls is for fan. So following energy consumption is assumed for a typical standard air-conditioned office (Good practice).

Table W.2: Annual delivered energy consumption of good practice air-conditioned office (standard type)

Air-conditioned office (Standard)	Heating (kWh/(m^2.yr))	Cooling (kWh/(m^2.yr))	Ventilation (kWh/(m^2.yr))
Good practice	77.60	14.00	28.50